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The Influence of Soil Moisture Regimes and Atmospheric Environments on transpiration and the Energy Status of Water in Plants

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THE INFLUENCE OF SOIL MOISTURE REGIMES AND ATMOSPHERIC ENVIRONMENTS ON TRANSPIRATION AND THE ENERGY STATUS OF WATER IN PLANTS

by

Sampatrao A. Gavande

A dissertation submitted in partial fulfillment
of the requirements for the degree

of

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Approved:

[redacted]

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INTRODUCTION

Plant responses to different soil moisture regimes have been extensively studied. Because of interactions between the soil, plant and climatic factors, few convincing generalizations concerning the influence of soil water on the transpiration of water by plants have been established. Generally single factors or at most the interaction of two have been studied at any one time. Useful theories describing the conditions of water retention in plant tissues and movement of water through plants have been proposed. Equally useful theories have been suggested for describing the retention and transmission of water in soil. The integration of these theories and their applications to evapotranspiration remains to be elucidated. This indicates a need for studying the total free energy path that causes water transport from soil to atmosphere through plants.

Two interrelated categories of processes or factors, atmospheric desiccation and rate of soil water uptake, need to be studied simultaneously. The energy status of plant water, herein called total plant water potential, in conjunction with soil water potential appears to be critically involved in the process of water transfer through the soil-plant-atmosphere system. Plant water potential is the best criterion for detecting the degree of plant water stress.

By studying water retention and flow properties of both plants and the supporting soil, one may be able to find relations that will help to predict the behavior of plants as they remove water from soil. For example, water retention characteristics of drought resistant plants may suggest reasons why some desert plants survive desiccating conditions that cause death to more succulent plant species.

The major objective of this study was to investigate the influence of soil water potential and atmospheric environment on both the transpiration rates and components of the plant water potential.

REVIEW OF LITERATURE

The influence of both environment and soil moisture conditions on water balance in plants may be explained on the basis of the energy relations of plant, soil and atmospheric water. Several reviews that have included partial discussion on application of energy principles have appeared and theoretical analysis is making continuing progress (Penman, 1956; Slatyer, 1957b, 1960, 1963; Lemon, 1963; Philip, 1957; Taylor, 1964; Gardner, 1960, 1964; Gardner and Ehlig, 1962, 1963). However, many of the environmental-plant relations are not quantitatively understood (McCloud et al., 1964) and until they are, only a limited description of the influence of environment on plant water balance can be made. The internal water balance of a plant is determined by a combination of the environmental factors affecting its growth (Hagan, 1955; Kramer, 1959). It is necessary to study the response of plants to environmental variations in order to obtain a more complete understanding of crop responses to different soil moisture conditions (Hagan et al., 1959).

Some physiological responses of the plant are directly controlled by internal water balance and only indirectly by soil moisture content (Kramer, 1959). However the internal water balance and actual degree of water stress in plants depend upon the relative rates of both water absorption and transpiration (Kramer, 1959, 1963; Slatyer, 1960, 1963). Since transpiration depends in part upon atmospheric conditions, the plant water balance must be influenced by a combination of soil, plant and atmospheric factors.

Some individual factors influencing water availability to plants as conceived by Jamison (1956) are: (a) plant factors of drought resistance, rooting depth and ramification, plant vigor, state of growth; (b) climatic factors of evaporation and transpiration losses as influenced by air temperature, air humidity, fog, wind and light; and (c) soil factors of moisture tension, osmotic pressure of the soil solution, ions in the soil solution and moisture conductivity relations.

In order to provide a broader basis for expression of entire soil-plant-water systems, and recognizing that diffusion pressure deficit (DPD) and its companion terms are conceptually units of Gibbs free energy of water in the plant system, several authors (Broyer, 1947; Edlefsen, 1941; Slatyer and Taylor, 1960; Taylor and Slatyer, 1961) have suggested terminologies based directly on thermodynamic quantities. This provides a flexible terminology that permits factors other than pressure and solute concentration to be included when necessary. Taylor and Slatyer (1961) considered the partial specific Gibbs free energy, which they called water potential to be the most useful term. They indicated that water potential of plants or soils in an isothermal system was made up of at least three components: solute potential, matric potential and pressure (turgor) potential. This terminology seems most appropriate and will be used herein.

Any control which the plant exercises upon transpiration operates largely through variation of stomatal aperture (Allerup, 1960; Halevy, 1960; Smith and Buchholtz, 1962; Stoddard and Miller, 1962). The dehydration of the leaf tends to close the stomata on most plants at a rather definite relative turgidity (Ehlig and Gardner, 1964; Gardner, 1965;

Kettallapper, 1963). Slavik (1958) observed both stomatal and cuticular transpiration to be related to the magnitude of the water potential of leaf and to a greater degree to the rate of increase of this deficit.

Slatyer (1957a) pointed out that the influence of low soil moisture on transpiration varies greatly among plants and is conditioned by evaporating conditions, sensitivity of stomatal closure, and availability of water for absorption. As the soil dries out, stomata close earlier each day (Kramer, 1949), and the transpiration decreases (Kozlowski, 1949; Slatyer, 1956), but the water deficits increase and extend longer into the night.

The transpiration and the accompanying water uptake are basically functions of the radiant energy input at the leaf surfaces, whenever water is freely available in the soil (McCloud et al., 1964; Hofmann, 1956; Neale, 1956). Energy gradients between the plant and its atmospheric environment depend largely on the presence or absence of radiation and the vapor pressure difference between the plant and the atmosphere (Raschke, 1960). The temperature of the plant leaf determines the saturation vapor pressure of the evaporating surface and hence plays a major role in the vapor exchange between the plant and the atmosphere.

The atmospheric evaporative demand is shown to influence the relation between the transpiration rate and soil water content. The accumulative water use was significantly different between two evaporative demands, reflecting a higher rate of water use at high evaporative demand (Peters, 1960). Studies under field conditions by Denmead and Shaw (1962) have shown how both soil capillary conductivity and atmospheric evaporative demand interact to influence transpiration rates.

Results of Gardner and Ehlig (1962) show that the soil water potential at which soil water conductivity becomes limiting depends on the plant and the soil texture. They failed to include atmospheric demand for water. They concluded that when soil water potential was above -60 Joules/kg the impedance to water movement was largely in the plant; when soil water potential was below -200 Joules/kg the movement in soil became the limiting factor.

Under constant potential evaporation the relation between soil water content and transpiration is characterized by a constant transpiration rate independent of soil-water potential until the latter drops below a critical value characteristic of the given soil-plant system and the transpiration rate (Gardner, 1965). At this soil water potential the corresponding plant water potential reaches the value at which stomata close. This may occur before permanent wilting point (Wallace and Stout, 1961). As the soil continues to dry and soil water potential decreases, the transpiration decreases in a curvilinear fashion with a rather rapid initial decline followed by a more gradual reduction in rate (Bahrani and Taylor, 1961; Denmead and Shaw, 1962; Gardner, 1965; Jarvis and Jarvis, 1963b; Perrier et al., 1961). According to Williams and Shafter (1955) transpiration of barley and rye was controlled largely by soil moisture level, but immediate past history of water availability also had an effect.

The internal water status of a plant is not uniquely determined by soil moisture alone (Kramer, 1959, 1963; McCloud et al., 1964). Veihmeyer (1927, 1956) and Veihmeyer and Hendrickson (1927, 1950) have argued that water is equally available to plants in drying soil down to permanent wilting point (PWP) where the water suddenly becomes unavailable. According to this view, physiological processes and growth would be essentially unaffected in drying soil, until PWP was reached. Subsequent to the work of Veihmeyer and Hendrickson, a preponderance of evidence has accumulated which indicates that metabolism and plant growth are influenced by even mild water deficits in plant tissues and that such internal water deficits usually occur long before drying soil approaches PWP (Richards and Wadleigh, 1952; Stanhill, 1957; Vaadia et al., 1961). These differences in concept may have developed because of variations in experimental methods and inadequate or incorrect evaluation of actual water deficits in plants under investigation (Kramer, 1963). In addition the experimental data may not have been correctly evaluated in some cases. Disagreement over the degree of water availability in drying soil may have existed partly because of differences in water retention relations for different types of soil (Kramer, 1949), in root development or in climate or combination of all (Hagan et al., 1957, 1959).

The effect of soil moisture on a few plant processes has been studied, and the relation of soil water supply to some physiological processes has been reviewed (Richards and Wadleigh, 1952; Vaadia et al., 1961). In most of these studies the physiological processes were simply correlated to soil moisture content. Generally no attempt was made to measure soil or plant water potentials or to relate them to physiological processes. When the effects of water deficits on plant processes are being studied, internal water balance should be determined so that a quantitative measure might be known for the extent of water deficit existing in the plant (Kramer, 1959, 1963).

Rutter and Sands (1958) studied water balance in two to three year old *Pinus silvestins* plants grown at four levels of soil moisture potential. Decrease in soil moisture potential caused a decrease in leaf water potentials, a decrease in transpiration, a decrease in number of open stomata and a decrease in the length of time they remained open during the day. Large differences in osmotic pressure between the roots and leaves which result due to variations of atmospheric environments have been found (Iljin, 1957). When soil water supply was kept favorable for plant growth and leaves were subjected to variable atmospheric relative humidity, the osmotic pressure values of roots remained more or less constant, even though the dryness of the air caused a progressive increase in osmotic pressure values of the leaves (Iljin, 1957). Gardner and Ehlig (1963) found that the differences between the plant water potential and soil water potential in a drying soil tended to remain constant, thus implying that soil water potential had a marked influence on the plant water potential. In another study, very little dependence of leaf water potential upon soil water potential was found until the soil water suction reached 2.5 atmospheres (Gardner and Nieman, 1964) whereas at high soil suctions the plant water potential depended markedly upon soil water potential.

Internal water balance and turgidity are closely related to the rates of some physiological processes that control the quantity and quality of plant growth (Kramer, 1959). A technique for measuring relative turgidity (Slatyer, 1957a; Barrs and Weatherly, 1962) suggest that a change in the turgidity of leaves during a given period reflects the inequality in absorption and transpiration during that period (Weatherly, 1950, 1951). Slatyer (1957a) found that as the total soil moisture stress (TSMS) increased, the degree of turgidity that plants are able to maintain decreased. Decreases in relative turgidity in turn profoundly influence various physiological processes of the plant (Kozlowski, 1964).

Generally there is a decrease in leaf turgidity during the day and recovery of leaf turgidity during the night (Slatyer, 1957a; Weatherly, 1950, 1951). Sometimes plants are unable to recover full turgor overnight after experiencing moisture stress during the day. Consequently, the turgor status at dawn reflects the atmospheric and soil moisture conditions affecting the plant during the preceding 24-hour period or longer. Turgor is also reported (Slatyer, 1963) to be influenced by diurnal changes in osmotic pressure in the plant.

The maximum turgor that can be developed in a plant is limited by soil water potential (Taylor, 1964). The turgor potential is the difference between the matric potential plus solute potential minus the soil water potential whenever soil is the source of water for the plant (Taylor, 1964). The relation between turgor potential and relative turgidity of plants has been found to be non-linear (Gardner and Ehlig, 1965). Thus the studies relating physiological responses to relative turgidity may be misleading.

Increasing attention has been given to the relation between the water content of the leaf and the water potential (Jarvis and Jarvis, 1963c; Weatherly and Slatyer, 1957). As the water potential in the plant leaf decreases, there seems little doubt that growth processes are affected (Brix, 1962; Gardner and Nieman, 1964; Gingrich and Russell, 1957; Jarvis and Jarvis, 1963a, 1963b). Closing of the stomata for the species studied by Ehlig and Gardner (1964) appeared to coincide with the inflexion point in the water content--water potential curve at about -13 to -15 bars. This corresponded to a turgor potential of about 2.5 bars. This was also the water potential at which marked wilting symptoms were observed. While it has been usually assumed that wilting corresponded to a value of zero turgor potential, the data of Ehlig and Gardner (1964) indicated that wilting may occur at a value for the pressure potential somewhat greater than zero.

METHODS AND PROCEDURES

Details of apparatus and measurement in growth chamber

A fine sandy loam soil was packed in medium-sized containers (22 cm in diameter x 22 cm deep). The bottom of each container contained a layer of small gravel 3 to 5 cm deep. Several tomato or orchard grass plants were placed in each container and grown in the greenhouse. When fully grown, they were transferred to a growth chamber. Plants were at least 10 weeks old before measurements were started. Each plant was used for several tests, spaced at 1-2 week intervals. Orchard grass was generally clipped after each test and allowed to regrow before succeeding tests. Soils were kept under high moisture potential near field capacity except when the soil water relations were under investigation.

The growth chamber was maintained at constant temperature, relative humidity, and light intensity for a series of determinations; then the environmental conditions were changed to give another evaporating condition for another series of measurements. During the experimental period, air temperature, relative humidity, and light intensity were 86°F, 30 ± 4 percent R.H., and 0.180 calories/cm^2/min respectively for one series and 70°F, 60 ± 4 percent R.H., and 0.18 calories/cm^2/min for the second series. Temperature and relative humidity were controlled by refrigeration system and changes in temperature and relative humidity were continuously recorded on a hydrothermograph. Light intensity was controlled by an equal number of infrared bulbs and fluorescent tubes and measured with a radiometer. The light was automatically turned on and off at the desired time to provide 14 hours daylight and 10 hours dark period. While in the controlled environment chamber, both the plant species were subjected to different soil moisture regimes established by applying irrigation water when soil water potential in the pot reached -10 Joules/kg, -50 Joules/kg, -100 Joules/kg, -500 Joules/kg and -1000 Joules/kg.

Transpirational losses were determined by weighing the plants and their containers daily. Accuracy of the balance used was 1/32 lb. Surface evaporation from the soil in which tomatoes grew was made negligible by covering the surface around the tomato stem with aluminum reflecting foil. Orchard grass itself provided a thick cover on the soil surface so that no aluminum foil was used on these pots. Soil water potentials were measured with tensiometers and gypsum resistance blocks made according to the design of Cannel and Asbell (1964). Vacuum gauge type tensiometers (Irrometers) were used at high soil water potentials.

Although an attempt was made to provide similar growth environment and growth media to all plants except for the variables under study, some dissimilarities in plants were noticed with respect to shape, size, and total surface area. Hence it was felt that the water use rates could be best expressed by relative transpiration rates obtained by taking a ratio ($E_a/E_a{}^o$) of actual transpiration rate (E_a) with that of maximum transpiration rate ($E_a{}^o$). Measurements were made and samples taken for measuring plant water potential and associated experiments early in the morning on days in which samples were made.

Effort was made to ensure that the soil moisture treatments would not be confounded with nutrient status by fertilizing all pots with standard nutrient solution.

It was observed that tomato plants made very good growth under high temperature of 86°F and low R.H. (30 percent), but they did not do so well under high humidity and low temperature conditions. Although insecticides were used, some damage by insects such as mites, aphids and white flies was noticed. Grasses did extremely well under both the treatments except that occasional occurrences of rust appeared under high humidity conditions.

Details of apparatus and measurements in constant temperature room

Vapor pressure apparatus consisting of a constant temperature bath and its accessories and control circuits are shown in figure 1. All sides of this bath were insulated by two layers of an insulating fiber board and aluminum foil. This bath was operated in a constant temperature room controlled to about ± 0.5°C in order to keep the control circuit stable and to avoid unnecessary variations in the bath temperature.

The temperature of the outer bath was first manually adjusted to approximately the desired temperature (26.1°C) with both constant cooling and constant heating devices and it was then maintained constant by thermoelectric relay-amplifier-powerstat system (figure 2). The temperature fluctuations were recorded frequently on a temperature monitoring circuit and found to be about ± 0.003°C for the outer bath. The variations damped out by the time they reached the inner bath, so that temperature fluctuations in the inner bath were less than ± 0.001°C as indicated by the monitoring circuit. By means of a precision resistance box (variable to 0.1 Ohm) in a wheatstone bridge control circuit it was possible to return to the same temperature at any time. The bridge circuit was thermally and electrically insulated in a styrofoam box.

The water potential of detached leaf tissues, termed as total plant water potential was measured with thermocouples made according to the design of Richards and Ogata (1958) and as described by Ehlig (1962).

1. Motor for stirrer
2. Stirrer rod--inner bath
3. Thermistor beads
4. Thermistor beads
5. Stirrer--outer bath
6. Sample containers
7. Water level--outer bath
8. Constant heating and cooling
9. Constant heating and cooling
10. Wheatstone bridge circuit
11. Wheatstone bridge circuit
12. Lid--outer bath
13. Water level--outer bath
14. Thermometer

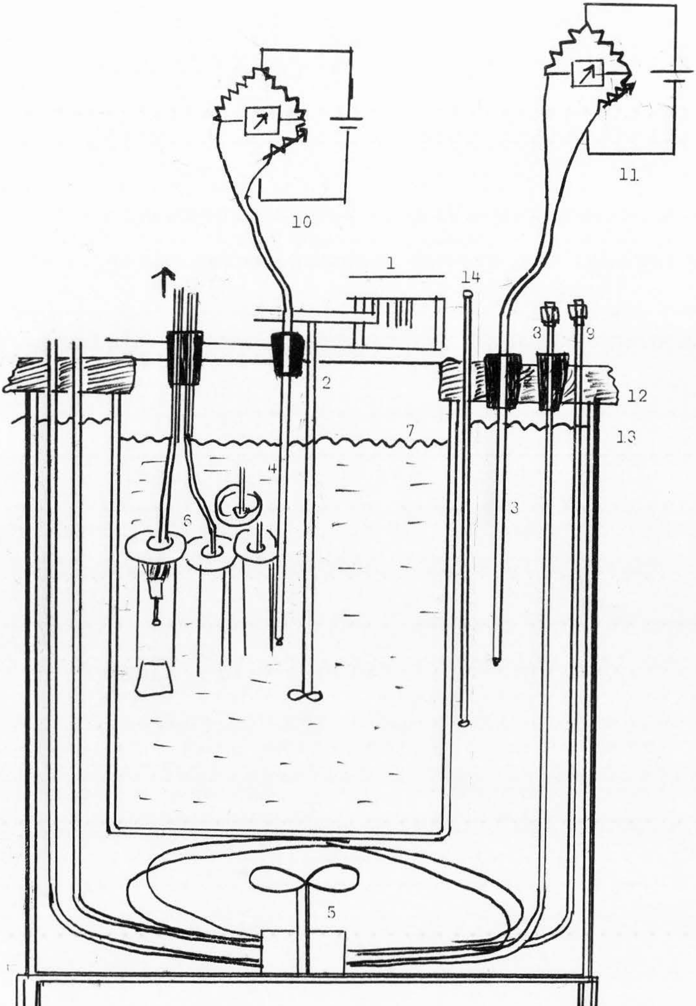
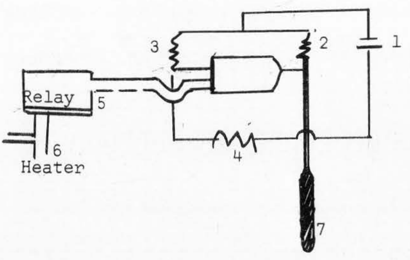


Figure 1. Diagram of constant temperature bath.



1. Mercury battery (1.36 Ω).
2. Known resistors (4000 Ω).
3. Known resistors (4000 Ω).
4. Adjustable resistance (4000 Ω).
5. Relay, Rheostat ek.
6. Heater coils
7. Thermistor (4000 Ω, Veco 32A1).

Figure 2. Temperature control diagram.

The thermal junction of the thermocouple consists of a silver loop with a radius of 2 mm and is attached to constantan and chromel-P wire (figure 3). The diameter of both the wires was 0.001 inch. Evaporation from a drop of water suspended inside the silver loop causes the cooling of the couple. The amount of cooling, which is an indication of water activity in the chamber, is measured by the e.m.f. output of the thermocouple. The e.m.f. output was measured on a potentiometer (Commander, Type - 9180 - B). The accuracy of the potentiometer used was on the order of $\pm 10^{-9}$ volts. An average value of positive and negative deflection on the galvanometer was taken as e.m.f. of that couple. All junctions were thermally controlled and shielded to avoid interference so that e.m.f. could be measured to $\pm 10^{-8}$ volt precision. The thermocouples were calibrated over KCl solution of different concentrations of known activity all at 26.1°C. The values calculated for water potentials from corresponding known activity are presented in table 1. Since the e.m.f. output of thermocouples is time dependent, it was necessary to make the measurements at time intervals corresponding to those for calibration curves. The calibration curves were checked at regular time intervals. It was necessary to allow a period of 6.5 hours for reaching temperature equilibrium inside the sample containers after they have been placed in the bath. The attainment of equilibrium point was indicated by a constant reading on the thermistor kept in the inner bath. All the thermocouple e.m.f. readings were taken when the point of resistance reached within the desired range. A sample calibration curve is shown in figure 4. After about six hours the output stayed constant for a period of one to two hours after which it was dropped gradually in some thermocouples because of loss of water from the

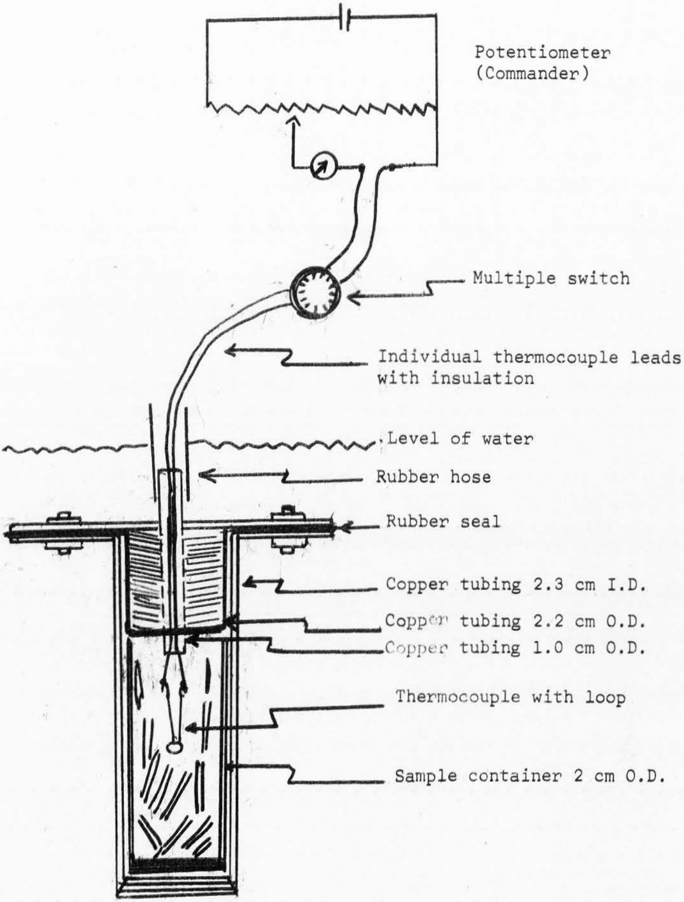


Figure 3. Schematic diagram of psychrometer.

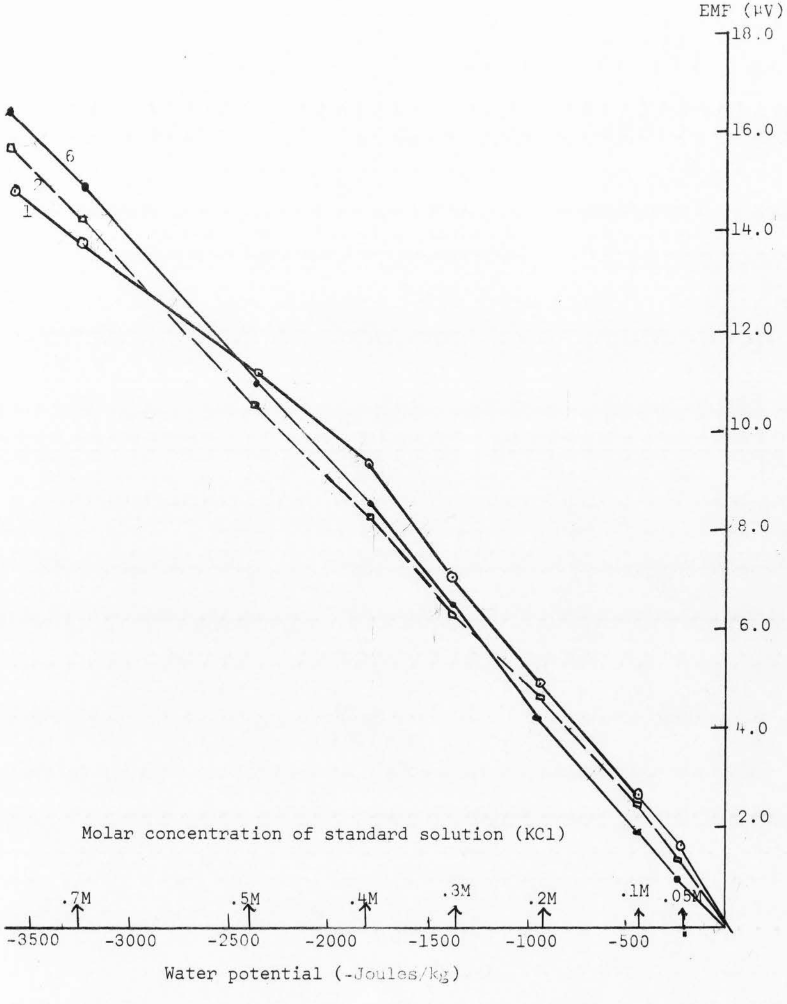


Figure 4A. Calibration curve for psychrometer relating potentiometer reading in μV to water potential in -Joules/kg or molar concentration of calibrating solution.

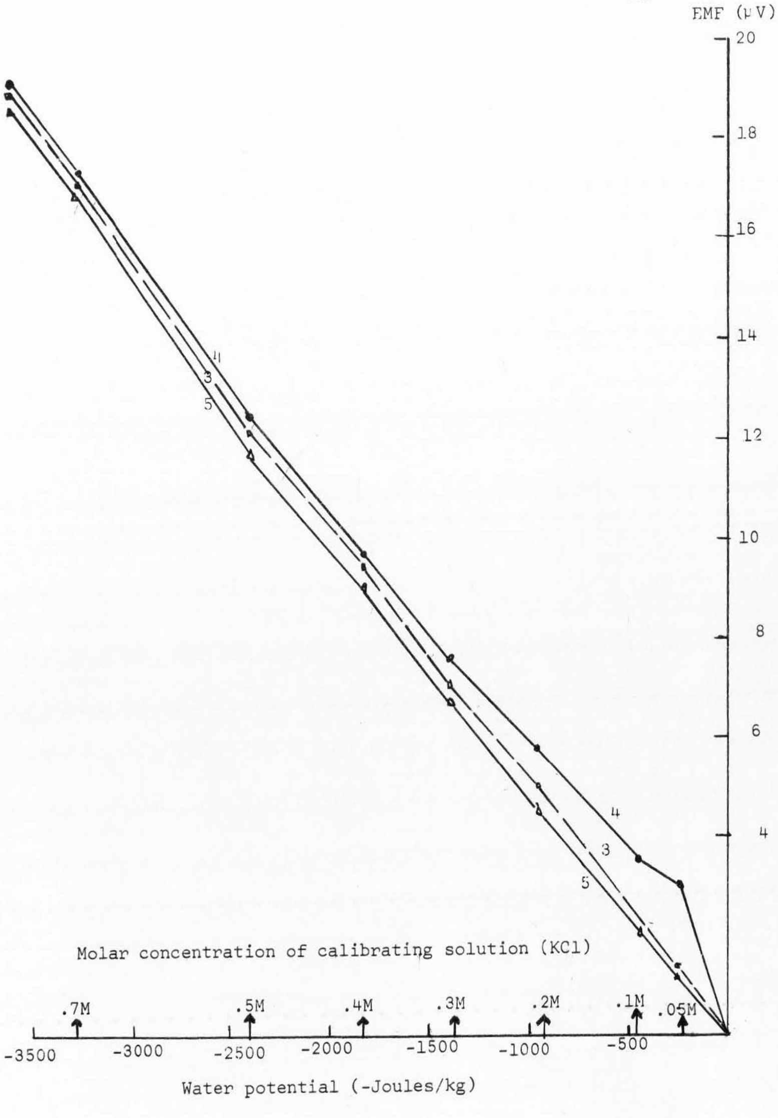


Figure 4B. Calibration curve for psychrometer relating potentiometer reading in µV to water potential in -Joules/kg or molar concentration of calibrating solution.

drop. Constant monitoring of the temperature in the inner bath, close to thermocouples, indicated that the time at which the e.m.f. became constant coincided with the time at which the temperature became stable in the inner bath. This was checked or observed, when there was no appreciable difference found on galvanometer readings when the positive and negative leads were interchanged. In some cases it was observed that a marked decrease in e.m.f. occurred when the water drop on the couple had become a flat water film inside the silver loop.

The method of Richards and Ogata (1958) was modified to permit complete immersion of the sample tubes (Kijne and Taylor, 1963). A similar modification was reported by Klute and Richards (1962). The desired leaf sample was sealed in the measuring chamber so that only heat could be exchanged with the surroundings.

The preparation of leaf material was critical. Several leaf sections were collected from a single plant (tomato) or group of plants (orchard grass) early in the morning when differences in leaves with respect to stomata opening and closing might be minimum. Each leaf was cut into two or more pieces (depending upon size of leaf) and whole experimental material was divided into homogeneous samples of a desired weight. One of the duplicate samples was used for relative turgidity measurements. Midribs and large veins were avoided in selecting leaf sections. Care was taken to line the sample in sample tubes all around the thermocouple and cover the wall surface of the chamber.

After the water potential measurements were completed, the tubes were covered with aluminum foil and then frozen with a mixture of dry ice and methyl alcohol, thawed and measurements on water potential were repeated using the same couples. Freezing kills the tissue membranes and destroys any turgor pressure. The potentials of the frozen tissue were then considered to be the osmotic potential (ψ_a) and include both solute and matric components of water potential. The values of turgor potential (ψ_p) were obtained by taking the difference between the osmotic potential (ψ_a) and the total potential (ψ). The values of ψ and ψ_a were taken from the appropriate calibration curve for the thermocouple used.

In separating the pressure potential from the osmotic potential on the basis of freezing and killing the tissue it was assumed that the only effect of killing was to eliminate the turgor potential of the cells. If there was any permanent change in the properties of the plant colloids as a result of freezing this influence would be shown in the turgor potential term. Likewise, if any effects resulted from metabolism of other plant life processes, they might appear in the same turgor potential term.

A further attempt was made to extract the solution from the tissue with Carver press assuming that matric (colloidal) attraction may remain with the solid portion and only the solute component will remain with the solution. However, separation of osmotic potential into its components (i.e., matric and solute potentials) was not satisfactorily achieved as can be seen from the data in appendix A, table 2 and figure 8. The discrepancy could be attributed to the presence of bound water.

Simultaneously, measurements on relative water content (R.T. %) at room temperature were made in a manner similar to that described by Barrs and Weatherby (1962). The duplicate samples from ψ measurement were weighed (fresh weight), floated on distilled water for five hours, surface dried with filter paper, reweighed (turgid weight), dried for one hour to constant weight in a vacuum oven at 80°C and reweighed (dry weight). The relative turgidity, expressed as percentage, was then obtained by

$$\text{R.T.} = \frac{\text{fresh weight - dry weight}}{\text{turgid weight - dry weight}} \times 100.$$

Rate of water uptake of detached leaves was found to be time dependent as well as moisture content dependent. For orchard grass, the increase in weight over original fresh weight was rapid for the first four or five hours. Then it became constant (figure 5A). The same relation held good for the change in dry weight (figure 5B). This observation was used to decide the suitable time for floating leaf sections on the water as well as for drying the samples to constant weight. For both the plants, the time used for floating samples was five hours and for drying was one hour.

Barrs (1965) showed that energy of respiration was involved in ψ measurements by the psychrometric method and correction in ψ values seemed necessary. Accordingly, a correction factor was obtained by making psychrometric measurements with dry junction (i.e., with no drop in silver loop) as a function of percentage relative turgidity (figure 6).

The mean values of plant water potential (ψ) were corrected by subtracting the values corresponding to the appropriate percentage relative turgidity from the measured ones as suggested by Barrs (1965).

The experimental observations show that variations in light intensity may cause differences in stomatal opening between leaves on the same branch (Sands and Rutter, 1958). This may be partly responsible for the observed differences in ψ versus RT relations. According to Sands and Rutter (1958) leaf water deficit at sunrise is a good index of the soil moisture condition that is experienced by the plant, since the changes in leaf water and transpiration rates are minimum at this time. For this reason plant samples

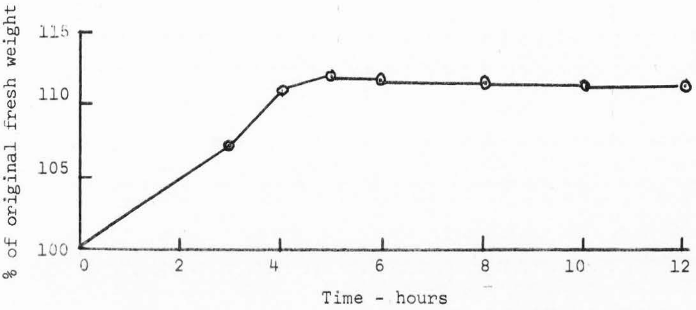


Figure 5A. Change of fresh weight with time after floating leaf sections of orchard grass on water.

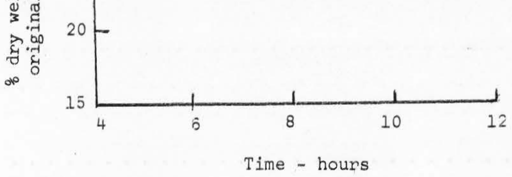


Figure 5B. Change in dry weight with time after floating leaf sections of orchard grass on water.

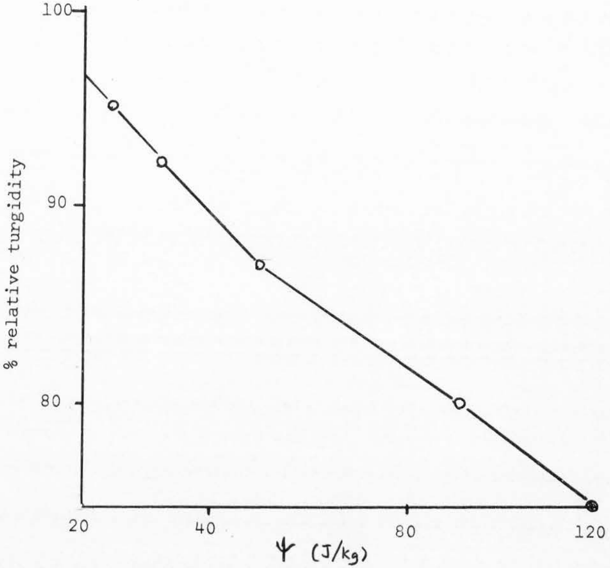


Figure 6. Corection factor for ψ due to respiration energy.

were taken once a day just before the lights came on.

EXPERIMENTAL RESULTS

Over a period of time all planned measurements of the total plant water potential and osmotic potential on leaf sections were made at the different soil moisture conditions under both sets of environmental conditions. These data are presented in appendix A, tables 3 and 4.

When plants are grown in their natural habitat, there is an apparent relation between the major ecological group of plants and their water potential quantities. Some of the relations are shown in the water retention or water release characteristics for various species grown under natural field conditions as shown in figure 7. For most of the species, the plant water potential decreased rapidly as the concentration of water in plant tissue was slowly reduced. Note particularly that mesophytic plants (tobacco, figure 7A) had a different shape of curve than woody plants (pine, maple and juniper).

The relations between various components of water potential and percent relative turgidity for corn plant leaves grown in greenhouse conditions are shown in figure 8A and appendix A, table 2A. The relations between various components of water potential and percentage relative turgidity for a tobacco plant during a drying cycle of nine days under greenhouse conditions is presented in figure 8B and appendix A, table 2B. The net difference between ψ and ψ_a is shown as ψ_p and that between ψ_a and ψ_π as ψ_θ. All components decreased with percentage relative turgidity.

Summary curves which compare the relative effects of soil moisture levels and evaporative demand on the energy status of water in plants in

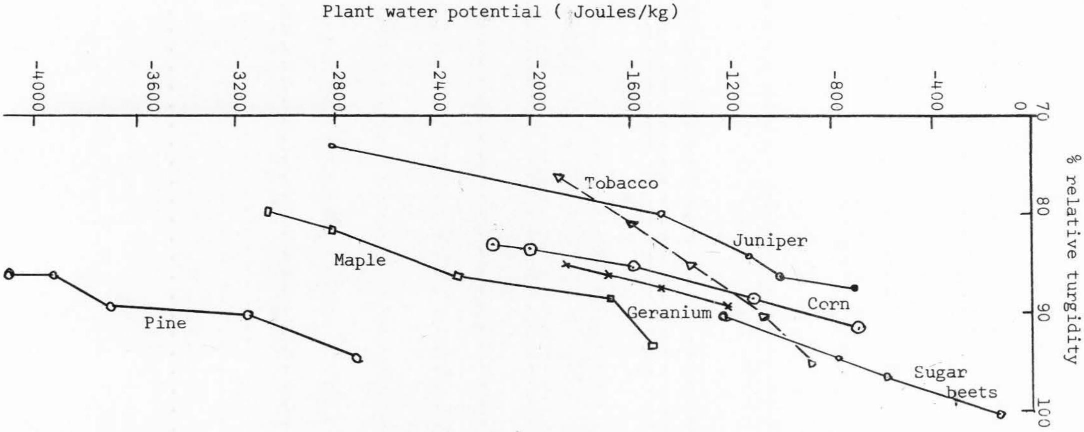


Figure 7A. Relation between plant water potential (-Joules/kg) and percentage relative turgidity for various species under field conditions.

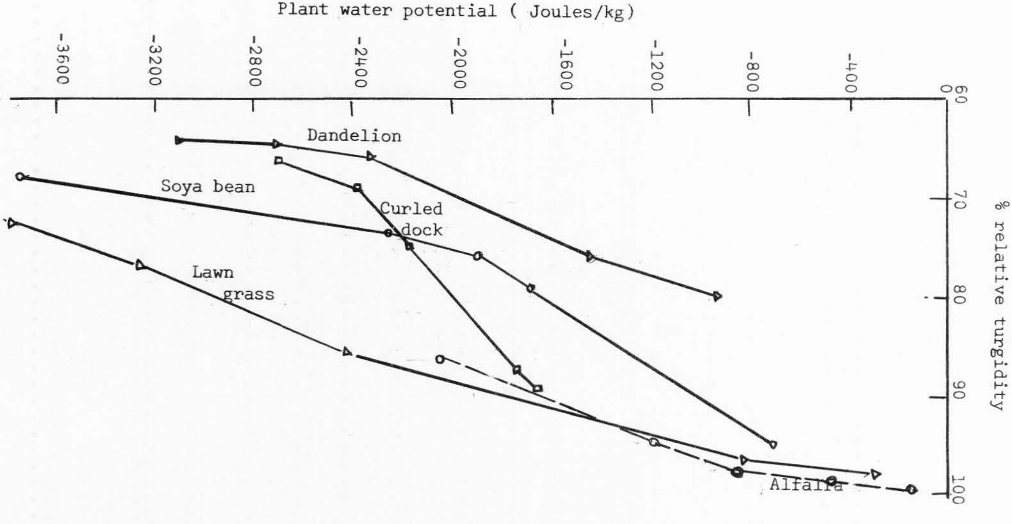


Figure 7B. Relation between plant water potential (-Joules/kg) and percentage relative turgidity for various species under field conditions.

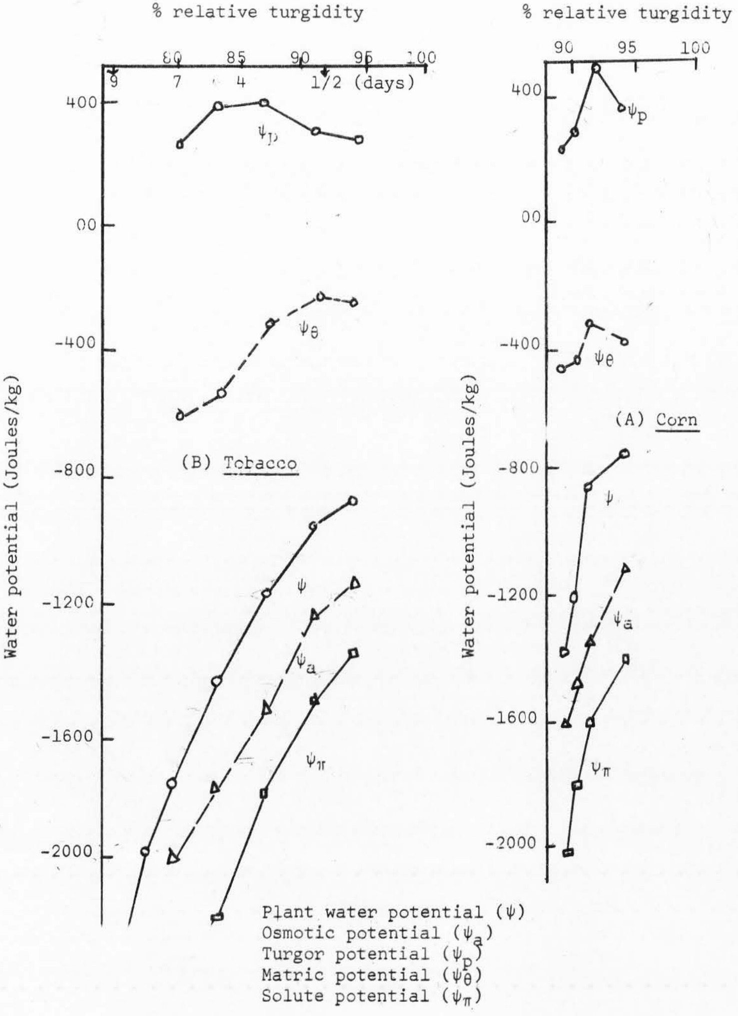


Figure 8A. Relation between components of plant water potential (-Joules/kg) and percentage relative turgidity for corn leaves under greenhouse conditions.

Figure 8B. Relation between components of plant water potential (-Joules/kg) and percentage relative turgidity for tobacco plants during one irrigation cycle of 9 days under greenhouse conditions.

terms of ψ, ψ_a, ψ_p and percentage relative turgidity are presented for orchard grass (figure 9A, B) and for tomato (figure 10A, B). At a given soil water potential (ψ_s) an increase in the intensity of evaporative conditions decreased the total water potential of the plants. The decrease in ψ that results from high evaporative demand in turn caused the normal decrease in soil water potential to be more rapid. It appears that the effect of evaporative demand was more pronounced on orchard grass than on tomato. High evaporative demand had marked influence in decreasing both ψ and ψ_a in orchard grass at all moisture levels. ψ_a for orchard grass was -1380 Joules/kg under conditions of 70°F and 60 percent R.H., whereas it was reduced to -2600 Joules/kg for same percentage relative turgidity and same soil moisture condition under conditions of 86°F and 30 percent R.H. Differences in ψ, ψ_a due to change in environment were less pronounced in tomato. Likewise, the ψ at zero turgor potential varied with plant environment, plant species and soil moisture treatment (figures 9, 10). It was lowered by high evaporative demand and by low ψ_s.

A relationship between leaf water potential and soil water potential for tomato and orchard grass is shown in figures 11A, B and 12A, B. The differences in ψ attributable to change in soil water potential were more pronounced for orchard grass than for tomato plants. The general pattern of decrease in ψ with decrease in ψ_s was the same for both plant species, except that the rate of decrease in ψ was influenced by different soil ranges and evaporative conditions. Decrease in ψ_a with decrease in ψ_s was less marked than for ψ. Changes in ψ and ψ_a for moderate evaporative conditions was relatively less than under more severe evaporative conditions. A smooth slope (figures 11B, 12B) was observed in gradient

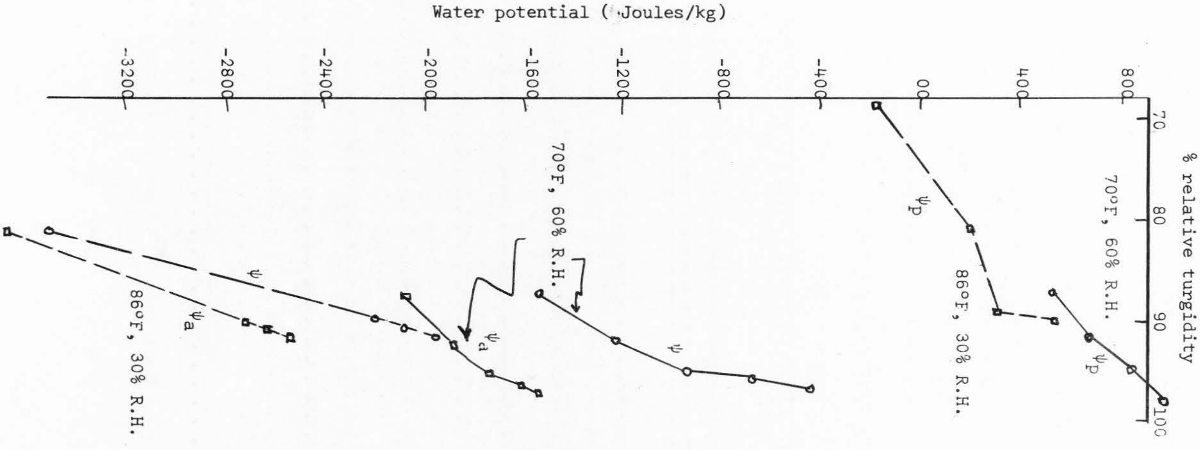


Figure 9A. Relation of % relative turgidity to various components of plant water potential for orchard grass leaves under two evaporative demand (-Joules/kg) conditions at two given soil moisture treatments (A:ψ_s = -1000 Joules/kg; B:ψ_s = -500 Joules/kg).

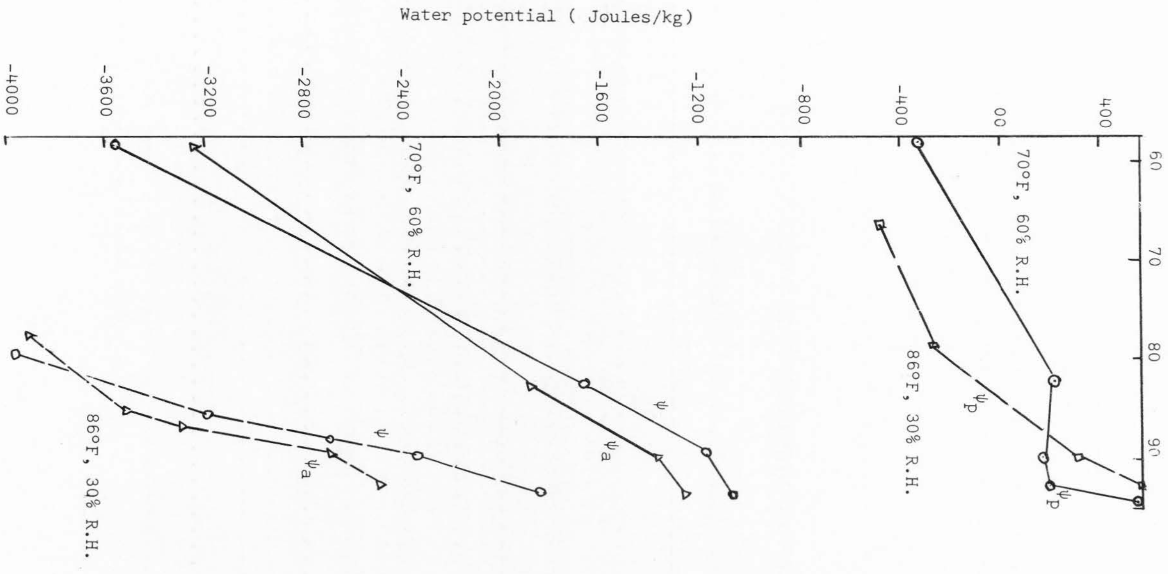


Figure 9B. Relation of % relative turgidity to various components of plant water potential for orchard grass leaves under two evaporative demand (-Joules/kg) conditions at two given soil moisture treatments (A:ψ_s = -1000 Joules/kg; B:ψ_s = -500 Joules/kg).

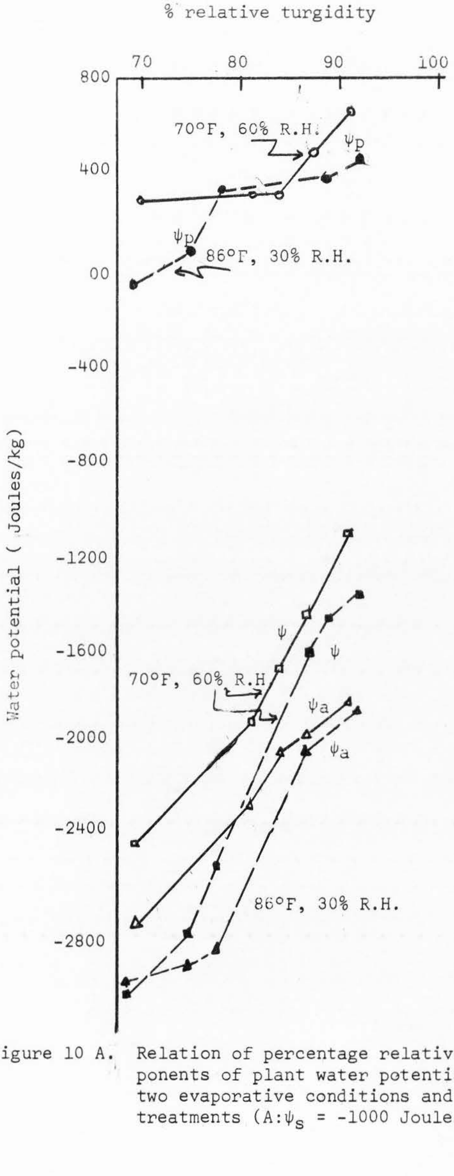


Figure 10 A. Relation of percentage relative turgidity to various components of plant water potential for tomato leaves under two evaporative conditions and two given soil moisture treatments (A:ψ_s = -1000 Joules/kg; B:ψ_s = -500 Joules/kg).

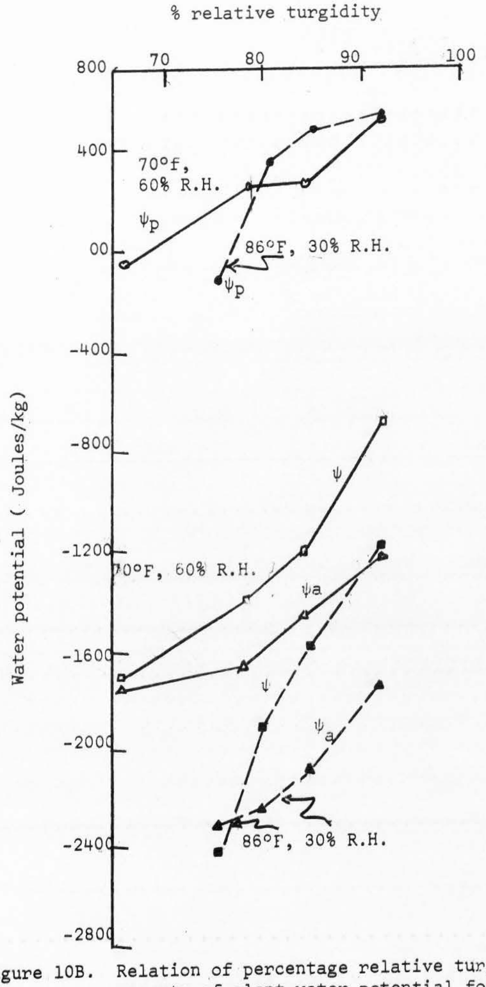


Figure 10B. Relation of percentage relative turgidity to various components of plant water potential for tomato leaves under two evaporative conditions and two given soil moisture treatments (A:ψ_s = -1000 Joules/kg; B:ψ_s = -500 Joules/kg).

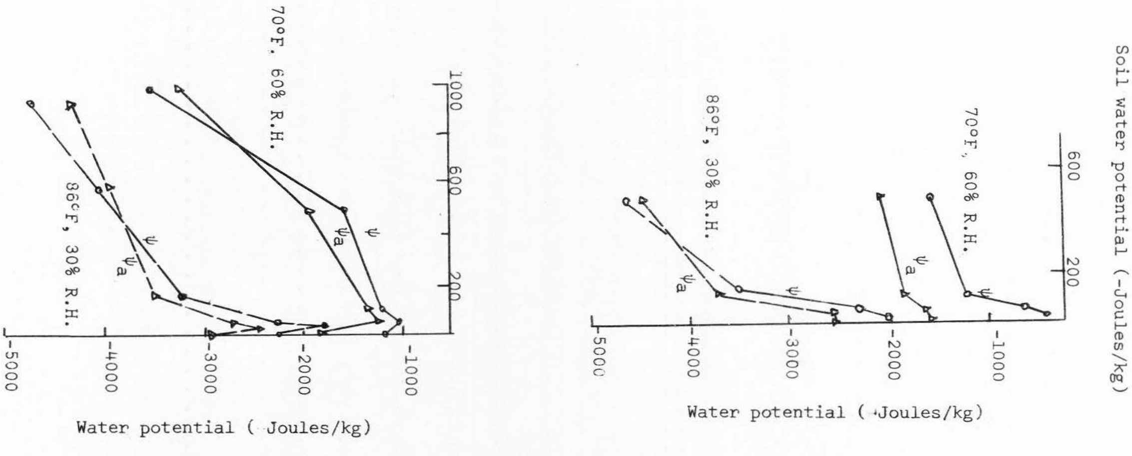
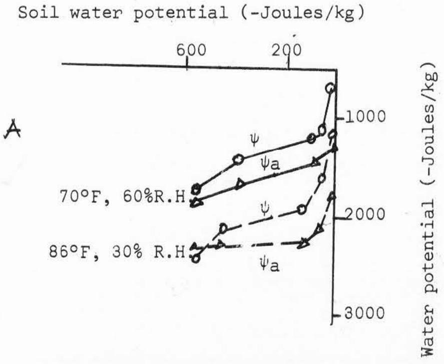


Figure 11A, B. Relation of soil moisture potential to plant water potential for orchard grass under two evaporative conditions and two given soil moisture treatments (A:ψ_s = -500 Joules/kg; B:ψ_s = -1000 Joules/kg).



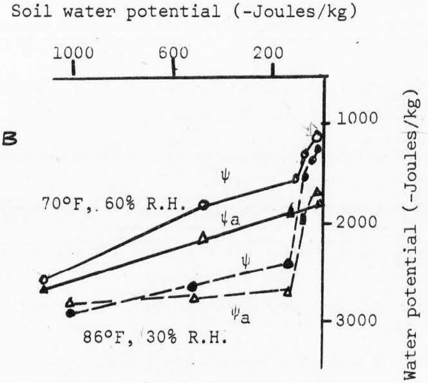


Figure 12A, B. Relation of soil moisture potential to plant water potential for tomato plant under two evaporative conditions and two given soil moisture treatments (A: ψ_s = -500 Joules/kg; B: ψ_s = -1000 Joules/kg) of ψ_a with change in ψ_s. In general, changes in ψ and ψ_a were rapid and abrupt over range of ψ_s between -50 Joules/kg and -150 Joules/kg for all cases. However, decrease in ψ was rapid for high evaporative conditions over the entire range of ψ_s. In fact, there was closer relation between ψa and ψ_s than between ψ and ψ_s. The occurrence of an inflection point (zero turgor potential point) was influenced by both the environmental and soil moisture effects. At high evaporative condition the inflection point was at -420 Joules/kg for -1000 Joules/kg soil moisture treatment or at -380 Joules/kg for -500 Joules/kg soil moisture treatment in orchard grass. Whereas for low evaporation the inflection point was at -750 Joules/kg (for ψ_s = -1000 Joules/kg) and it was not noticeable within the range at low evaporative condition for either plant species at ψ_s = -500 Joules/kg.

Figure 13A, B shows the relation of plant water potential and environmental conditions to relative transpiration rate for tomato and orchard grass at ψ_s = -1000 Joules/kg. At low evaporative demand, there was rapid decrease in relative transpiration rate in the vicinity of ψ = -1500 Joules/kg for orchard grass and when ψ was below -1700 Joules/kg, the transpiration was largely a function of external variables. In fact, ψ depended largely upon transpiration rate, whereas in tomato a close relation was observed between ψ and Ea/Ea° over the entire range of ψ. At high evaporative conditions there was close relation between ψ and E_a/E_a°, between ψ = -2600 Joules/kg (grass) and -4500 Joules/kg. In tomato relative transpiration rate dropped abruptly between ψ = -2400 Joules/kg and ψ = -2800 Joules/kg (figure 13B) for both evaporative conditions.

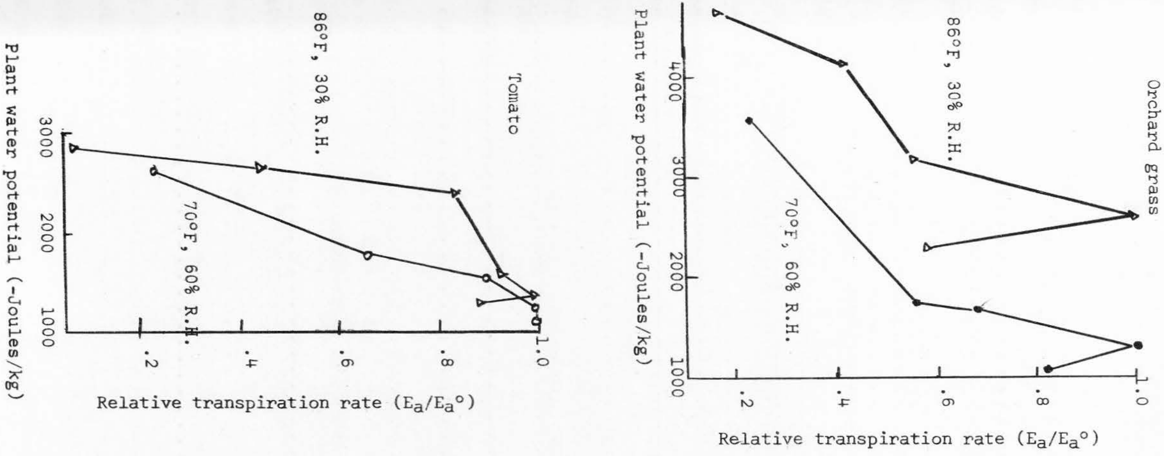


Figure 13. Relation of plant water potential to relative transpiration rate for orchard grass and tomato plant under two evaporative conditions at a given soil moisture treatment (ψ_s = -1000 Joules/kg).

Figures 14A, 14B, 15A and 15B show the quantitative dependence of relative transpiration rate on soil water potential under two evaporative demand conditions for tomato and orchard grass. Under high evaporative demand conditions, the transpiration rate decreased rapidly with decreasing soil water potential, until ψ_s = -100 Joules/kg, somewhere after field capacity when plants started suffering water stress. Below this ψ_s level the decline in transpiration rate was gradual. Under low evaporative conditions this decrease in ψ with decrease in ψ_s was gradual over most of the ψ_s range.

Summary curves showing daily fluctuations in ψ, ψ_s, and $E_a/E_a°$ are represented in figures 16 to 19 for both the crops and environments. The rate of transpiration was found to be inversely related to the water potential in the plant and soil. In general, the differences between the curves representing plant water potential and soil water potential get larger as the potentials decrease. In spite of this increase in water potential differences in soils and plants, the water use rates decreased as the soil dried out. The degree of these successive differences in ψ, ψ_s, and transpiration rates (for two consecutive irrigation cycles), under two different environments and different soil water potentials for tomato and orchard grass is obvious from figures 16 to 19. The nature and degree of slope of both ψ and transpiration rates with time representative curve found to vary with the frequency of irrigation, soil moisture treatment, species, and evaporative demand. The slopes for longer intervals, for drier conditions (say ψ_s = -1000 Joules/kg) and for high evaporative conditions (figures 17B, 19B) were steeper during any irrigation cycle than those for shorter intervals, wetter soil conditions (say ψ_s = -500 Joules/kg) and low evaporative demand (figures 16A, 18A). This steepness was even

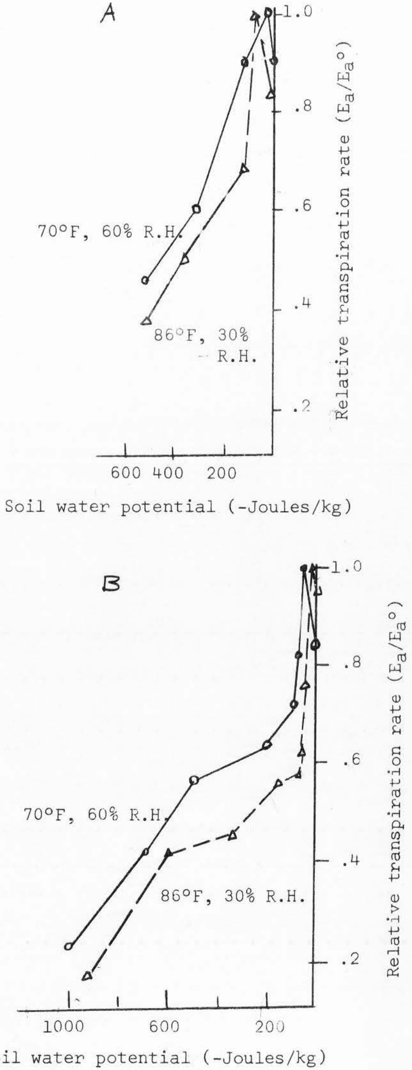


Figure 14A, B. Relation of soil water potential to relative transpiration rate for orchard grass under two evaporative conditions and two given soil moisture treatments (A:ψ_s = -500 Joules/kg; B:ψ_s = -1000 Joules/kg).

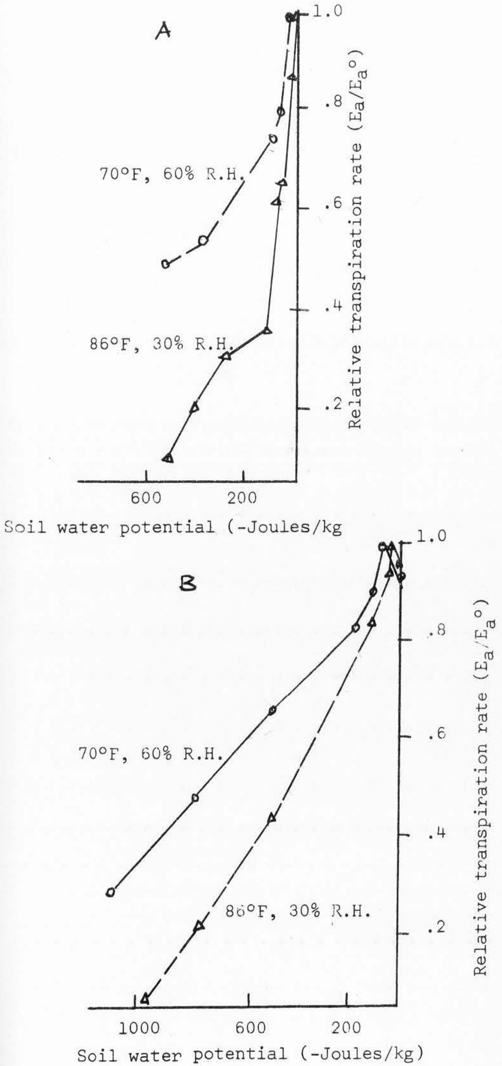


Figure 15. Relation of soil water potential to relative transpiration rate for tomato plant under two evaporative conditions and two given soil moisture treatments (A: ψ_s = -500 Joules/kg; B: ψ_s = -1000 Joules/kg)

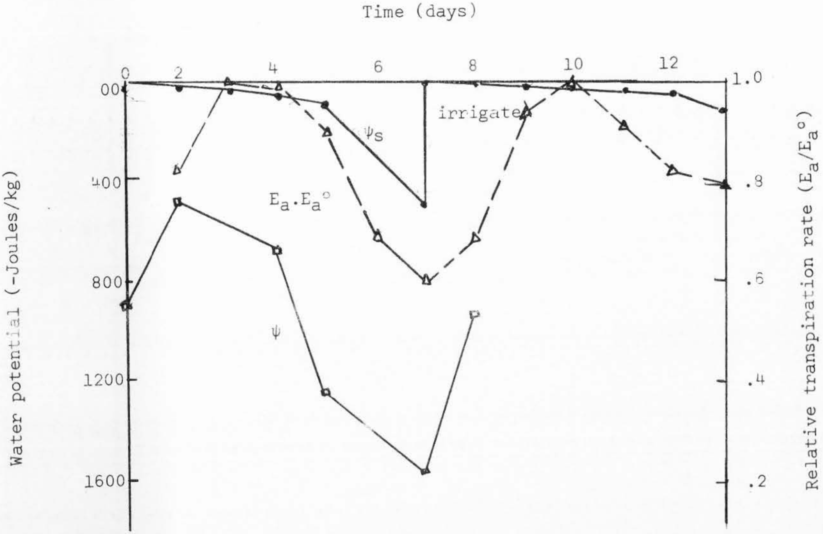


Figure 16A. A change in relative transpiration rate ($E_a/E_a°$) from orchard grass, plant water potential (ψ) and soil water potential (ψ_s) with time (days) under controlled conditions of T = 70°F, R.H. = 60 ± 4%, light intensity = 0.18 cal/cm^2/min at a given soil moisture treatment (ψ_s = -500 Joules/kg).

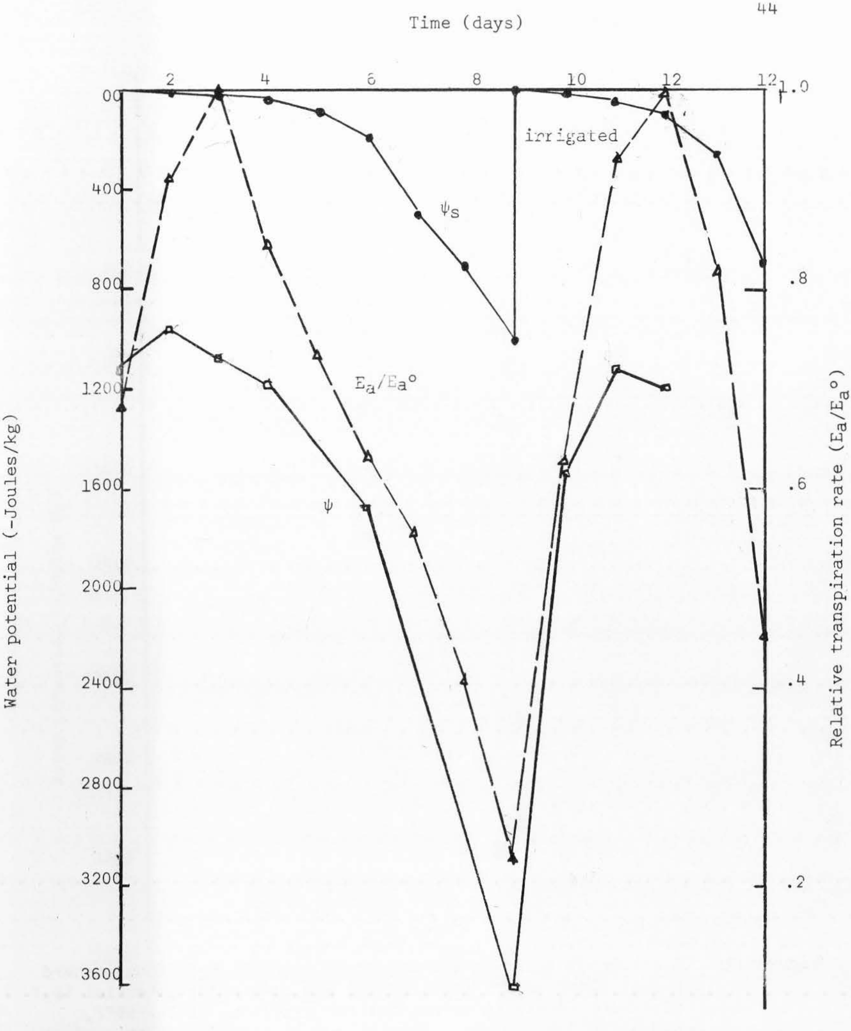


Figure 16B. A change in relative transpiration rate ($E_a/E_a°$) from orchard grass, plant water potential (ψ) and soil water potential (ψ_s) with time (days) under controlled conditions of T = 70°F, R.H. = 60 ± 4%, light intensity = 0.18 cal/cm^2/min at a given soil moisture treatment (ψ_s = -1000 Joules/kg).

Figure 17A. A change in relative transpiration rate ($E_a/E_a°$) from orchard grass, plant water potential (ψ) and soil water potential (ψ_s) with time (days) under controlled conditions of T = 86°F, R.H. = 30 ± 4%, light intensity = 0.18 cal/cm^2/min at a given soil moisture condition (ψ_s = -1000 Joules/kg).

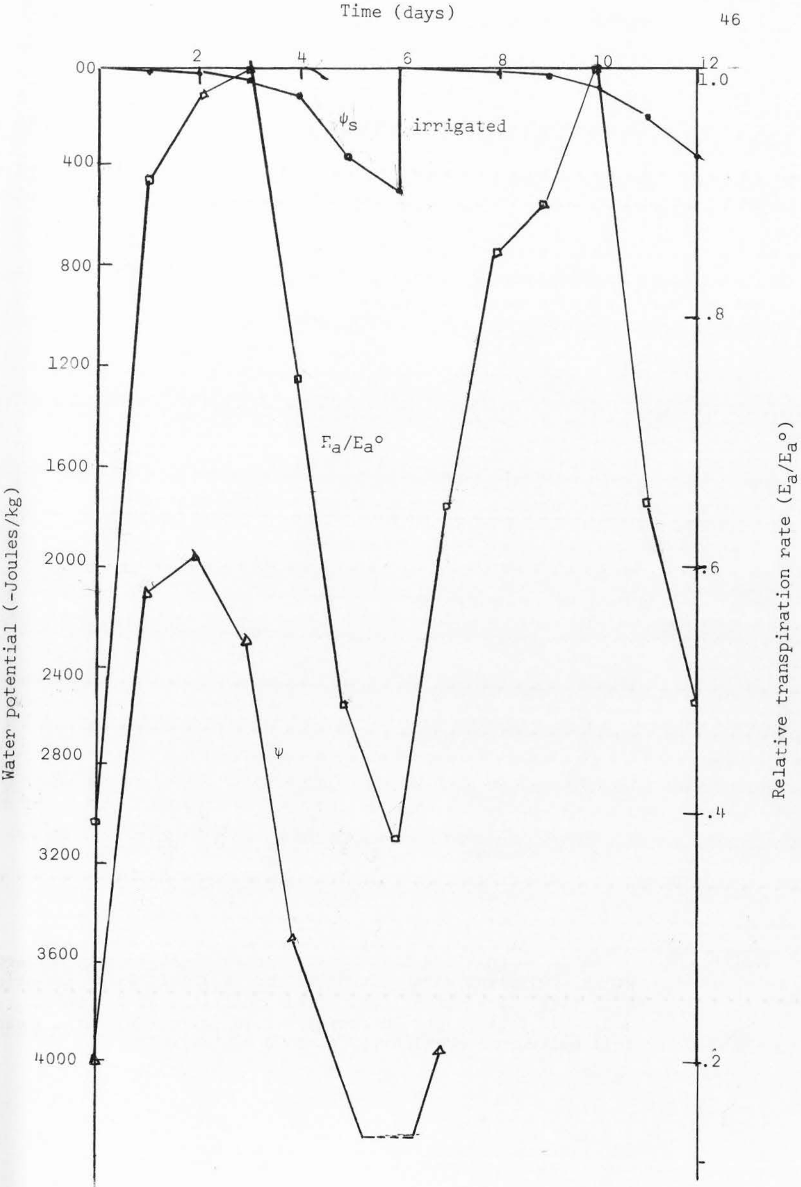
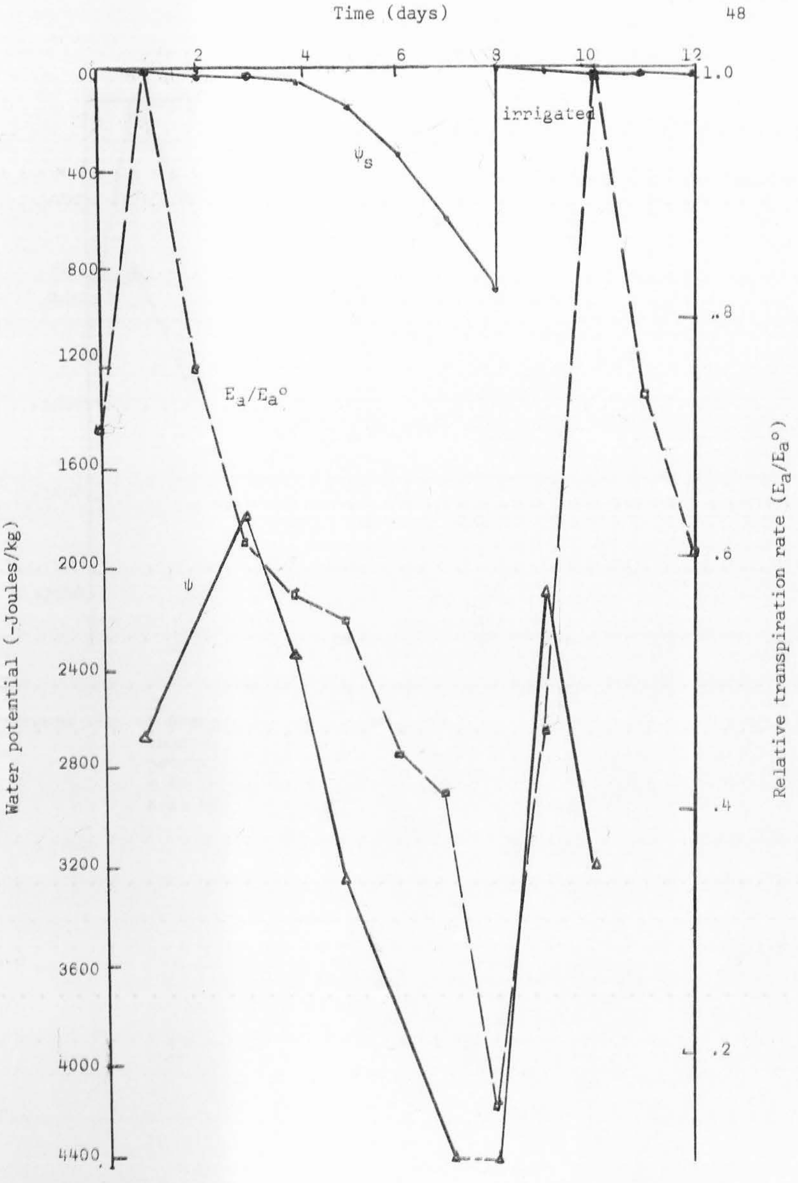

Time (days)
2
4
6
8
10
12
00
400
800
1200
1600
2000
2400
2800
3200
3600
4000
Water potential (-Joules/kg)
ψ_s
irrigated
$E_a/E_a°$
ψ
1.0
.8
.6
.4
.2
Relative transpiration rate ($E_a/E_a°$)

Figure 17B. A change in relative transpiration rate (E_a/E_a^o) from orchard grass, (ψ) plant water potential and (ψ_s) soil water potential with time (days) under controlled conditions of T = 86°F, R.H. = 30 ± 4%, light intensity = 0.18 cal/cm^2/min at a given soil moisture condition (ψ_s = -1000 Joules/kg).


Time (days)
2
4
6
8
10
12
00
400
800
1200
1600
2000
2400
2800
3200
3600
4000
4400
Water potential (-Joules/kg)
1.0
.8
.6
.4
.2
Relative transpiration rate ($E_a/E_a°$)
irrigated
ψ_s
$E_a/E_a°$
ψ

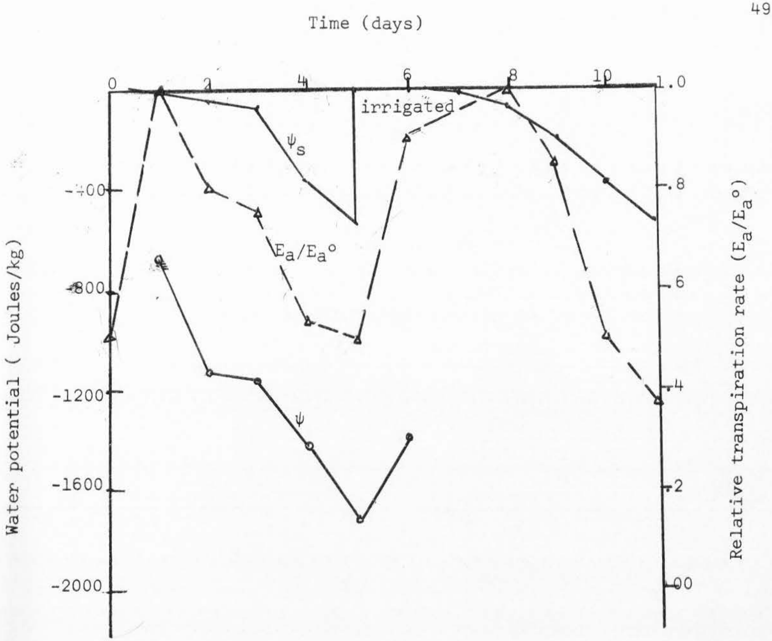


Figure 18A. A change in relative transpiration rate ($E_a/E_a°$) from tomato, (ψ) plant water potential and (ψ_s) soil water potential under controlled conditions of T = 70°F, R.H. = 60 ± 4%, light intensity = 0.18 cal/cm^2/ min at a given soil moisture condition (table 4A) ψ_s = -500 Joules/kg.

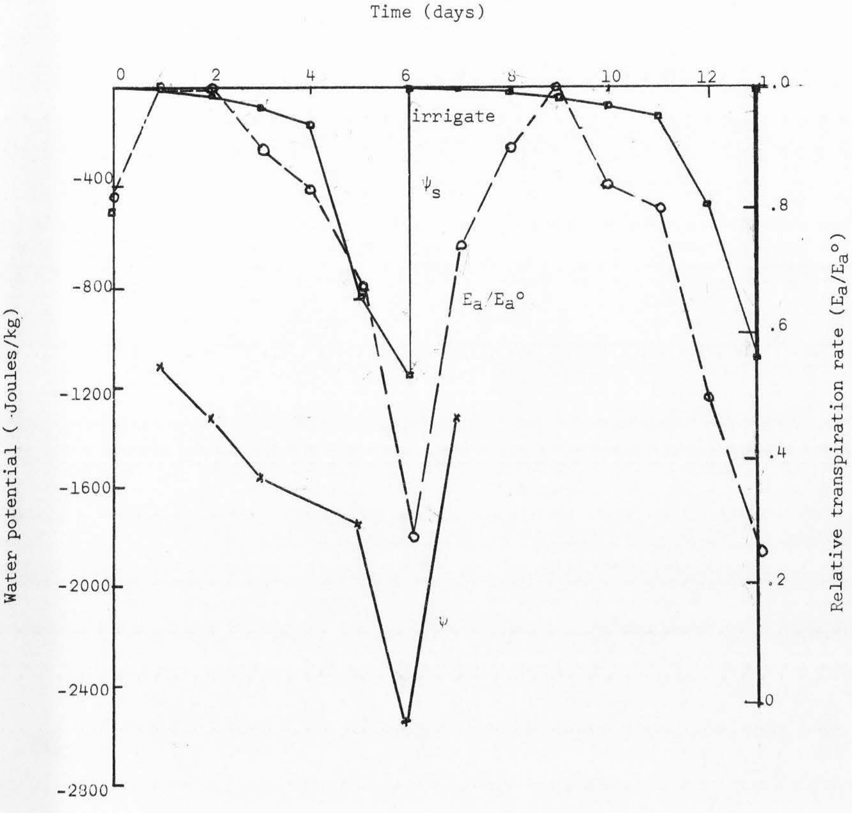


Figure 18B. A change in relative transpiration rate ($E_a/E_a°$) from tomato, plant water potential (ψ) and soil water potential (ψ_s) with time (days) under controlled conditions of T = 70°F, R.H. = 60 ± 4%, light intensity = 0.18 cal/cm^2/min at a given soil moisture treatment of ψ_s = -1000 Joules/kg.

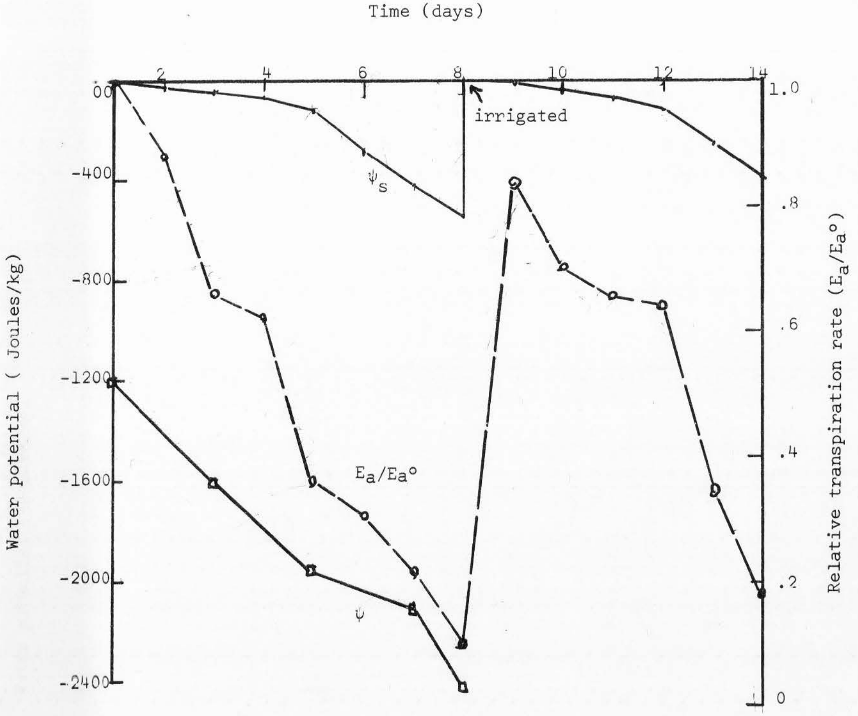


Figure 19A. A change in relative transpiration rate (E_a/E_a^o) from tomato, plant water potential (ψ) and soil water potential (ψ_s) with time (days) under controlled conditions of T = 86°F, R.H. = 30 ± 4%, light intensity = 0.18 cal/cm^2/min at a given soil moisture treatment (table 4) ψ_s = -500 Joules/kg.

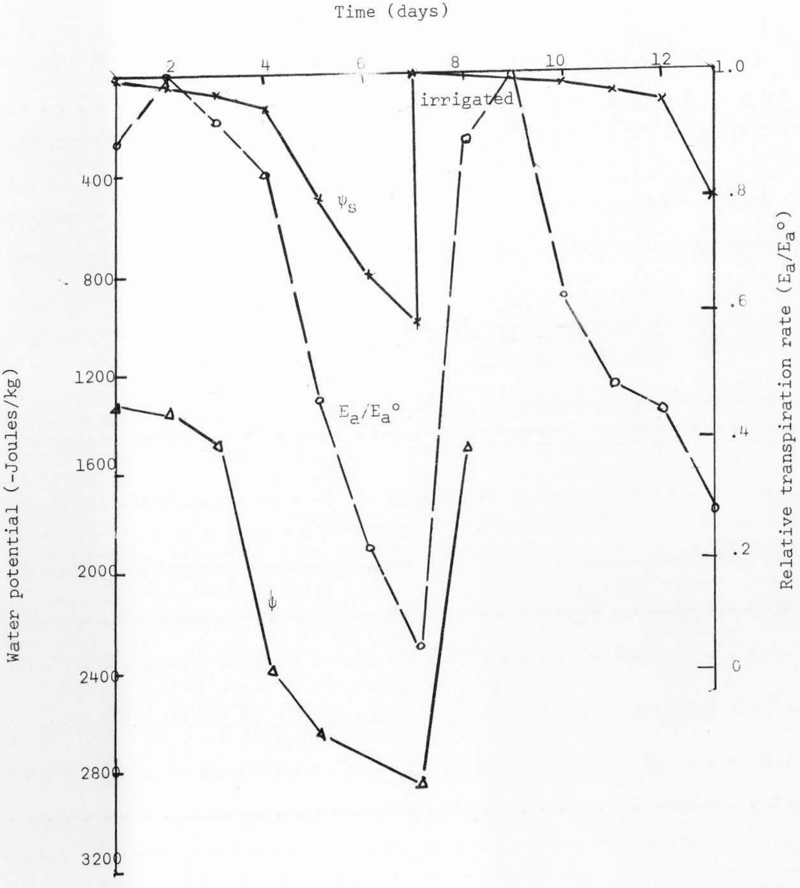


Figure 19B. A change in relative transpiration rate (E_a/E_a^o) from tomato, plant water potential (ψ) and soil water potential (ψ_s) with time (days) under conditions of T = 86°F, R.H. = 30 ± 4%, light intensity = 0.18 cal/cm^2/min at a given soil moisture treatment (table 4) ψ_s = -1000 Joules/kg.

greater for second or consecutive irrigation cycles.

DISCUSSION

The influence of different atmospheric environmental conditions on plant responses to decreasing ψ_s in terms of ψ, ψ_a, ψ_p, R.T. and $E_a/E_a°$ are of particular interest. The relation between these responses is also of considerable practical significance as the degree of turgidity at any one stress value is an indication of the physiological activity of the plant.

The measurements (appendix A, tables 3 and 4) on ψ, ψ_a, R.T. and $E_a/E_a°$ for individual samples show consistent soil moisture potential and evaporative demand induced changes. However, there was considerable variation in the individual ψ and ψ_a values with the same or nearly same R.T. and same ψ_s. To avoid this sampling variation sometimes leaves were cut into two halves and mixed so as to give a homogeneous sample and all the determinations on ψ and ψ_a were made in triplicate. A series of water potential measurements were made on leaf sections taken from branches of a single plant that was exposed to light. An attempt was also made to obtain all measurements continuously during one irrigation cycle. However, in some cases part of the data was introduced from consecutive irrigation cycles because of malfunctioning or changes in growth chamber. It was difficult to obtain a particular soil moisture potential on a particular day and corresponding to a particular time. It was necessary to use trial and error and experience in adding a definite amount of irrigation water at a particular time in order to achieve a particular soil water potential value when desired. Consequently, the water potential values listed in appendix A, tables 3 and 4, cover a range of values as indicated.

The quantitative results found in the experiments are similar to some of the results already reported in literature by Slatyer (1957a, 1957b, 1960), Gardner (1960, 1964), Gardner and Ehlig (1962, 1963, 1965), Ehlig and Gardner (1964) and Denmead and Shaw (1962) among others. Although most of these researchers have partly measured relations between relative leaf water content, soil water potential, plant water potential and transpiration rates, no one of them has measured influence of varying atmospheric environments on these relations. In addition, their experiments were conducted either in greenhouse or field conditions. In some of their experiments that have dealt with soil moisture stress effects, some factors influencing the internal water balance were controlled, while many others were not. Such experiments are difficult to evaluate in terms of actual internal plant water deficit.

Results from figures 9 to 19 show that atmospheric environments exert considerable influence on relations between internal plant water status, and transpiration rate as influenced by soil water potential. The effects of varying atmospheric environments on each of these relations are discussed below in detail:

Internal plant water status

Atmospheric environmental effects on relation of relative leaf water content to components of plant water potential are obvious from figures 9 and 10. Transpiration process removes water from plant tissue; unless this loss is immediately replaced, the remaining water in the tissue is at lower water potentials. The transpiration effect when it exceeds absorption, may thus be accompanied by reduction in turgor in plant tissues. One might predict that at high evaporative conditions caused by high temperature and low humidity, the effect on decreasing plant water potential with decrease in relative turgidity would be more than with low evaporating conditions. This is substantiated by figures 9 and 10 which indicate that under conditions favoring greater water losses from leaf surfaces the plant water potential diminishes linearly with the relative water content in leaves. The influence of atmospheric environment on reduction in plant water potential at a given percentage relative turgidity was more marked for ψ_s = -1000 Joules/kg treatments than for ψ_s = -100 Joules/kg or ψ_s = -500 Joules/kg treatments.

An interesting aspect of the R.T. versus ψ data of figures 9A and 10A is the marked differences which existed between the species as to the degree of water stress developed at a given level of relative turgidity with varying evaporative demand and vice-versa. In orchard grass, for instance, ψ was reduced to -1840 Joules/kg at a relative turgidity of 80 percent under low evaporative demand and 93 percent under high evaporative demand. Values of ψ = -4120 Joules/kg and ψ = -2000 Joules/kg for low and high evaporative demands respectively were reached when relative turgidity fell to 78 percent. Comparative data from tomato (figure 10A) showed that a value of ψ = -1200 Joules/kg was reached as relative turgidity fell to 88 percent for low evaporative demand and to 93.5 percent for high evaporative demand; whereas a relative turgidity of 90 percent in tomato induced ψ = -1100 Joules/kg and ψ = -1340 Joules/kg for low and high evaporative demands respectively.

Atmospheric environment influences relations of relative turgidity to both osmotic potential and turgor potential (figures 9 and 10). Turgor changes in plant system are caused mainly by changes in internal water content, which may have resulted from the lag of absorption behind transpiration. Changes in internal leaf water content affect turgor potential directly. The internal leaf water content in turn is influenced by accompanying changes in the concentration of cell sap. High evaporative demand may increase the concentration of cell sap and hence reduce osmotic potential in the plant. High evaporative demand may also indicate a build up of more soluble carbohydrates during the day. In addition, the effect of high evaporative demand on osmotic potential could be a reflection of the influence of higher temperature on hydrolysis of starches or some other process that affects the solute content of tissues.

Atmospheric environment influences relations between components of plant water potential and soil water potential (figures 11A, 11B, 12A and 12B). As mentioned earlier in review, internal water relations of a plant are not themselves specifically related to soil moisture. The present study suggests that the magnitude of internal plant water relations depends on a combination of soil water availability and atmospheric demand for water. Little direct effect of soil water potential on plant water potential was observed (figures 11 and 12). When the water potential in the soil was not limiting and stomata are assumed to remain open, the rapid reduction in or a non-linear decrease of plant water potential with decreasing soil water potential may be attributed to atmospheric environments. It is expected that high evaporative demand, when water potential in the soil is limiting, increases the rate of transpiration over absorption. Increased transpiration increases steepness of the water potential gradient between the plant and the soil as can be seen in figures 11 and 12. Under low evaporative conditions the decrease in ψ_s was gradual over most of the ψ_s range, whereas under high evaporative demand conditions, there was a rapid reduction in ψ with decrease in ψ_s to a particular value and a less rapid decrease below that value. From the results of figures 11 and 12 it is probable that there exists a certain low or nearly saturated ideal atmospheric evaporative condition, where a decrease in ψ with decrease in ψ_s would be linear; likewise there exists another extremely high evaporative condition, where this decline in ψ with ψ_s would be highly non-linear in nature. Such an interaction between atmospheric and evaporative demand and soil water potential in affecting water potentials in plants may explain why some investigators (McCloud, et al., 1964) have concluded that plants may undergo severe water stress even when the soil water potential is near field capacity if atmospheric desiccation is high and at other times encounter little moisture stress even though the soil water potential is low, providing the atmospheric evaporative conditions are also low.

On the days in which the previous soil moisture potential was relatively high (say ψ_s = -50 Joules/kg or ψ_s = -100 Joules/kg) and evaporative conditions were low, recovery in plant turgor was completed by dawn or when the lights came on. On the days of high evaporative demand and a very low previous soil water potential treatment (ψ_s = -500 Joules/kg or ψ_s = -1000 Joules/kg) the recovery in turgor was apparently not completed by dawn, the overnight period being too short. Thus the potential points corresponding to highest ψ and ψ_s values (i.e., a thermodynamic equilibrium point between ψ and ψ_s) varied with evaporative demand, ψ_s treatment and species.

The plant water potential at zero turgor was different for the two species and two evaporative demands as shown in figures 11 and 12. It also varied with soil water potential.

The atmospheric environment influenced osmotic potential more than either plant water potential or turgor potential, thus emphasizing the fact that the influence on plant water potential may be related to stomatal closure and turgor potential effect.

Atmospheric environment influences relations of both plant water potential and soil water potential to transpiration rate (figures 13A, 13B, 14A and 14B). As per Van den Honart's (1948) hypothesis, if the vapor phase change at the leaf-air-interphase is the location in the plant giving the greatest resistance and is limiting the movement of water through the tissue, then the rate of water loss would be directly proportional to the atmospheric demand or in turn net radiation. This would also mean that the temperature condition in the leaf would vary with atmospheric demand. In other words, increased air temperature will result in increased leaf temperature of the plants, which in turn will result in an increased saturation vapor pressure gradient from leaf to the air, thus increasing the transpiration. Such a dependence of transpiration on atmospheric evaporative demand is expected to be valid especially when soil water supply is ample and stomata are open during the day (figures 13 and 14).

When water potential in leaves becomes sufficiently low because of reduced soil water potential resulting from greater atmospheric demand for water, the stomata will likely close and water loss be reduced (figures 13A, B). Under these conditions, stomatal regulation serves to prevent desiccation and to partially control transpiration. Measurements of water loss from detached leaves (Ehlig and Gardner, 1964) showed that most of the stomata on a given leaf apparently close at about the same value of ψ. Figure 13A shows a rapid decrease in relative transpiration rate between ψ = -1300 Joules/kg and -1700 Joules/kg for orchard grass under low evaporative demand and between ψ = -1600 Joules/kg and -3100 Joules/kg for high evaporative demand, which was no doubt caused by increased resistance of tissue to desiccation resulting from decreasing plant water potential. Throughout this moist region, the transpiration rates were largely controlled by external environment. Below this value transpiration rate decreased gradually as ψ decreased. The initial ψ values would be on the same order at which ψ becomes ψ_s dependent.

As discussed above, the higher the level of evaporative demand, the more the effect of decreasing ψ_s could be observed. Thus figures 14A, B 15A, B indicate that under conditions favoring greater water losses from leaf surfaces, the transpiration rates decrease as ψ_s decreases. Atmospheric environment also influenced ψ_s level when the actual transpiration fell below maximum transpiration rate. For low evaporative conditions the actual transpiration rate fell below maximum transpiration rate when ψ_s in the root zone reached -80 Joules/kg. For high evaporative conditions this decline in transpiration rate occurred at about ψ_s = -20 Joules/kg.

It is difficult to say to what extent the relationships indicated in figures 13 to 15 would be unique. The differences in pattern of transpiration rates under different evaporative conditions may have been pronounced because of non-uniform root habits of orchard grass and tomato and differences in soil conductivities between ψ_s = -1000 Joules/kg and ψ_s = -500 Joules/kg treatments.

It can be concluded that high atmospheric evaporative demand in terms of high air temperature and low humidity increases leaf temperature, which in turn increases steepness of saturation vapor pressure gradient from the leaf outward to the adjacent air, thus increasing transpiration rate. Increased transpiration in turn decreases plant turgor by lowering relative water content in the leaves, develops and steepens water potential gradient through plants from evaporating surfaces of leaves to absorbing surfaces of roots. Thus the factors affecting water supply and water demand are related to plant water potential, which influences the extent to which water potential gradient can be maintained.

Lag of plant water potential behind soil water potential

The hypothesis that the internal water deficits in plants occur when absorption lags behind transpiration was examined by studying the daily march of changes in ψ, ψ_s and Ea/Ea° while the plant was allowed to draw water from a drying soil under two different evaporative conditions. From figures 16 to 19 it can be noted that under both evaporative conditions, the transpiration and plant water potential at first wilting lagged behind soil water potential.

When the wilted plant is irrigated water potential in the soil is abruptly increased; because of slow recovery in turgor change in plant water potential may not be so abrupt. Both transpiration rates and plant water potential for a particular soil water potential come to normal in the second or third day after irrigation.

Although two processes are partly interdependent, absorption is controlled by soil factors, and water loss chiefly by atmospheric factors, and they often occur at different rates. As shown in figures 16 to 19, the rate of absorption even in moist soils tends to lag behind rate of transpiration possibly because a water potential gradient needs to be established in order for plants to remove water from soil. In addition, this lag may have developed because of inability of plant to take up water as a result of protoplasmic injury caused by a water deficit.

The quantitative lag of ψ and E_a/E_a° behind ψ_s was modified by varying atmospheric environments. For a given ψ_s treatment the lag was more marked when the atmospheric environments were of a nature that will maintain high rates of transpiration and vice-versa.

There is no reason to expect any symptoms of damage to protoplasm and reduction in plant turgor or a lag of both transpiration and ψ behind ψ_s as long as water uptake does not lag appreciably behind water loss from the leaves. This may be the case under low evaporative demand condition for a particular range of ψ_s and species. In this case both soil water conductivity and permeability of the plant are expected not to limit the relative rates of transpiration and absorption thus giving less steepness to water potential gradient in the plant and the soil. Thus in figures 16A, 18A little or no lag in ψ and E_a/E_a° behind ψ_s was observed.

If we assume that the permeability of plant tissue remains constant, the water potential difference between plant and soil will need to increase rapidly, if the transpiration deficit is to be met and transpiration is to remain constant. From figures 16 to 19, it is clear that the differences between ψ and ψ_s get larger as the atmospheric desiccation increases and as the soil water potential decreases.

As the water potential in the leaves decreases, turgor potential is reduced and leaves get dehydrated. We may assume that such a dehydration effect is accompanied by reduction in stomatal opening and a decrease in tissue permeability. As a result transpiration should decline and consequently lag behind soil water potential.

CONCLUSIONS

1. The plant water potential, osmotic potential, turgor potential and transpiration losses from two plant species were influenced by both soil water potential and atmospheric evaporative demand. The effect was greater on osmotic potential than on either plant water potential or turgor potential.
2. Both transpiration rate and plant water potential tend to follow soil water potential but lag behind it.
3. The respective differences were significant between time and plant water potential, soil water potential, and transpiration rate for the two species, orchard grass and tomato.
4. The combined effect of atmospheric evaporative demand and soil water potential was more marked than either effect alone.
5. High evaporative demand caused a more marked influence on the moisture retention and transpiration characteristics of plants grown at higher soil water potentials than occurred under low evaporative demand conditions.

SUGGESTIONS FOR FUTURE RESEARCH

1. The relations between ψ, ψ_s and E_a/E_a° need to be studied under a wider variety of conditions.
2. Correlation between transpiration rates and factors controlling it, especially tissue permeability and factors of plant environment, and ψ needs to be made.
3. Emphasis should be laid on perfecting the techniques for measuring plant water balance and evaluating its relationship to evaporative demand on one hand and to supply on the other.
4. There is a need to determine at what levels of ψ and ψ_s, and at what evaporative conditions conductivity of water to soil and plant becomes limiting.
5. Emphasis may be given to the relation between water deficits and metabolism and the manner by which decreased water potential influences reaction rates and induces shifts in the physiological pattern of the tissues.
6. There is a need to find functional relationships of several components of plant water potential. We need to know the exact nature, behavior and magnitude of the various components of water potential and their relations to water content especially in the presence of bound water in plant tissues.
7. Further investigation is necessary to confirm the hypothesis that the non-linearity in the relations between plant water potential and soil water potential in a drying soil may be attributed to

atmospheric environments or reduced soil conductivity or combination of both. It also remains to be shown whether or not the non-linearity is simply a gradient induced influence on the permeability of plants or simply a mechanical effect.

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APPENDICES

Appendix A

Experimental results

Table 1. Values of the free energy of water over KCl at 26.1°C by an equation, $\Delta\mu_w = RT \ln P/P_o$

Molarity of KCl solution	Activity $a_w = {}^{P}/_{P_o}$ at 26.1°C[a]	Water potential $\Delta\mu_w$ = (-J/kg)
.05 M	0.998306	-241.64
0.1 M	0.996670	-462.0
0.2 M	0.99343	-1095.0
0.3 M	0.990251	-1385.4
0.4 M	0.9870761	-1836.48
0.5 M	0.983890	-2268.2
0.7 M	0.97747	-3157.46
1.0 M	0.968068	-4542.8

[a] These values were obtained by a small temperature correction for 26.1°C from the relation between water activity and molarity of KCl solutions from the data given by Taylor, et al. (1961).

Table 2. Relation between components of water potential (ψ = total water potential, ψ_θ = matric potential, ψ_p = solute potential, ψ_a = osmotic potential, ψ_π = turgor potential) and percentage relative turgidity (R.T.) under greenhouse conditions.

2 A: Corn

R.T. %	ψ (-J/kg)	ψ_a (-J/jg)	ψ_p (+J/kg)	ψ_π (-J/kg)	ψ_θ (-J/kg)
94.2	760	1120	360	1400	380
91.6	880	1360	480	1600	340
90.2	1200	1460	260	1860	400
89.4	1420	1600	180	1060	460

2 B: Tobacco

Days	R.T. %	ψ (-J/kg)	ψ_a (-J/kg)	ψ_p (+J/kg)	ψ_π (-J/kg)	ψ_θ (-J/kg)
1/2	94	840	1150	310	1380	230
	91	960	1220	300	1420	200
4	87	1180	1520	340	1800	280
	84.4	1480	1800	320	2320	520
7	80	1800	2020	100	2600	580
	78	2000	-	-	-	-
9	75	2400	-	-	-	-

Table 3. Relation of soil water potential (ψ_s), relative transpiration rate (E_a/E_a°) to the components of water potential (ψ = total plant water potential, ψ_a = osmotic potential, ψ_p = turgor potential) for orchard grass under controlled conditions of varying environments and soil moisture treatments. (The additional data on E_a/E_a° and ψ_s was obtained as long as growth chamber was continued to operate.)

A. Evaporative condition A: 70°F, 60% R.H. and 0.18 cal/cm^2/min light intensity.

N days 1	E_a/E_a° 2	ψ_s (-J/kg) 3	R.T. % 4	ψ (-J/kg) 5	ψ_a (-J/kg) 6	ψ_p (+J/kg) 7	t 2 d.f.
	1) ψ_s = -10 J/kg						
				260	760	500	
	1.0	10	97.4	190	800	610	12.55**
				420	1080	660	
				290	880	590	
	2) ψ_s = -10 J/kg to -50 J/kg						
				320	720	400	
	1.0	10	96.5	370	880	510	
				540	950	410	
				410	850	440	12.53**
	.93	50	95.8	580	1100	520	
				860	1280	420	
				930	1320	390	
				790	1233	443	11.26*
	3) ψ_s = -10 J/kg to -100 J/kg						
				320	950	630	
1	1.0	10	96	390	1080	690	
				400	1150	750	
				370	1060	690	19.93**
2	.78	50	95	540	1080	540	
				640	1330	690	
				590	1205	615	
				590	1205	615	14.20**

Differences between means of ψ and ψ_a are
* = Significant at 5% level
** = Significant at 1% level

Table 3. (cont.)

1	2	3	4	5	6	7	8
3	0.95	100	91.7	1040	1600	560	
				1160	1600	440	
				1220	1800	580	
				1140	1666	526	12.128**
	4) ψ_s = -10 J/kg to -500 J/kg						
1	-	500			before irrigation		
2	.82	10	97	320	1500	1180	
				470	1560	1090	
				590	1650	1060	
				460	1570	1110	30.807**
3	1.0	25	-	-	-	-	
4	.98	50	94.4	630	1460	830	
				650	1600	950	
				730	1650	920	
				670	1570	900	24.98**
5	.90	100	91.5	1200	1800	600	
				1120	1700	580	
				1430	2000	570	
				1250	1833	583	66.17**
6	.69	300	-	-	-	-	
7	.60	500	87	1500	2100	600	
				1390	2020	630	
				1860	2100	240	
				1583	2073	490	3.91
8	-	-	-	-	-	-	
9	.94		95.2	690	1600	910	
				820	1600	780	
				1320	2100	780	
				943	1766	823	19.03**
10	1.00	25					
11	.91	30					
12	.82	50					
13	.78	120					
14	.70	360					
15	.60	550					

Table 3. (cont.)

1	2	3	4	5	6	7	8
	5) ψ_s = -10 J/kg to -1000 J/kg						
1	.68	0	-	-	-	-	-
2	.91	10	94.6	1020	1600	480	
				1120	1600	480	
				1320	2100	780	
				1153	1766	613	6.95*
3	1.0	20	-	-	-	-	-
4	.82	40	93	1180	1240	60	
				950	1200	250	
				1200	1500	300	2.783
5	.73	95	89.4	1250	1400	150	
				1150	1300	150	
				1230	1470	250	
				1210	1390	183	5.495*
6	.635	200	-	-	-	-	
7	.57	500	82	1710	1800	90	
				1530	1700	170	
				1880	2200	480	
				1706	1900	246	7.115*
8	.41	700	-	-	-	-	
9	.23	1000	58	3600	2700	800	
				3750	3550	200	
				3500	3500	000	
				3616	3250	-333	1.38
10	.64	10	91	1530	1880	350	
				1410	1700	280	
				1610	2100	490	
				1516	1886	373	6.075*
11	.925	50					
12	1.0	100					
13	.82	250					
14	.45	700					
15	.23	1000					
16	.74	10					
17	.91	40					

* = Significant at 5% level
** = Significant at 1% level

Table 3. (cont.)

B. Evaporative condition B: 86°F, 30% R.H. and 0.18 cal/cm^2/ min light intensity

N days 1	E_a/ E_a^o 2	ψ_s (-J/kg) 3	R.T. % 4	ψ (-J/kg) 5	ψ_a (-J/kg) 6	ψ_p (+J/kg) 7	t 2 d.f. 8
-	-	10	94	970	1740	770	
				1220	1900	680	
				1020	1820	800	
				1103	1820	717	19.90**
	2) ψ_s = -10 J/kg to -50 J/kg						
1		10	93	1430	1800	370	
				1020	1590	570	
				1360	1750	390	
				1270	1713	443	6.96*
		50	89	1540	1890	350	
				1490	1760	270	
				1590	1900	310	
				1540	1850	310	13.41**
	3) ψ_s = -10 J/kg to -100 J/kg						
1		10	92.2	1530	1990	460	
				1630	2060	430	
				1520	1810	310	
				1560	1960	400	8.73*
		50	88.5	2140	2460	320	
				2290	1640	350	
				2170	2400	230	
				2200	2500	300	8.32*
		100	85.5	2390	2690	300	
				2600	2810	210	
				2330	2540	210	
				2440	2680	240	8.00*

Table 3. (cont.)

1	2	3	4	5	6	7	8
	4) ψ_s = -10 J/kg to -500 J/kg						
0	.38	500		Before irrigation			
1	.91	10	90	2210	2600	390	
				2250	2900	650	
				2230	2750	520	
				2230	2750	520	6.93*
2	.98	10	91	1870	2500	630	
				2120	2600	480	
				1950	2580	630	
				1980	2560	580	7.59*
3	1.00	50	89.4	2350	2580	230	
				2300	2670	370	
				2250	2430	180	
				2300	2580	260	4.57*
4	.68	120	80	3270	3500	230	
				3810	3900	90	
				3540	3700	160	
				3540	3700	160	3.96*
5	.51	360	-	-	-	-	
6	.38	500	68	4650	4400	-250	
				4600	4450	-150	
				4700	4425	-275	
				4650	4425	-225	5.897*
7	.65	10					
8	.82	25					
9	.89	40					
10	1.0	80					
11	.65	200					
12	.49	350					
13	.37	500					
14	.90	15					
15	.91	40					
16	.97	50					
17	1.0	100					

Table 3. (cont.)

1	2	3	4	5	6	7	8
	5) ψ_s = -10 J/kg to -1000 J/kg						
0	.71	1000		Before irrigation			
1	1.0	15	88	2750	3400	650	
				2250	3200	950	
				2550	3300	750	
				2516	3300	784	8.88*
2	.76	10					
3	.62	10	92.6	1760	2420	660	
				1800	2380	580	
				1930	2460	530	
				1830	2420	590	15.64**
4	.58	50	89.4	2460	2750	290	
				2260	2650	390	
				2420	2700	280	
				2380	2700	320	8.98*
5	.56	160	86	3080	3400	320	
				3460	3610	150	
				3240	3550	310	
				3260	3520	260	4.71*
6	.45	350					
7	.42	600	78	4190	3950	-240	
				4080	4000	- 80	
				4300	3750	-550	
				4190	3900	-290	3.417
8	.17	920	66	4750	4250	-500	
				4600	4300	-300	
				4900	4275	-625	
				4750	4275	-475	5.021*
9	.47	0					
10	1.00	10					
11	.74	15					
12	.64	20					
13	.43	45					
14	.38	70					
15	.36	300					

Table 3. (cont.)

1	2	3	4	5	6	7	8
16	.302	500					
17	.174	650					
18	.10	940					

* = Significant at 5% level
** = Significant at 1% level

Table 4. Relation of soil water potential (ψ_s), relative transpiration rate (E_a/E_a°) to the components of water potential (ψ = total plant water potential, ψ_a = osmotic potential, ψ_p = turgor potential) for tomato plant under controlled conditions of varying environments and soil moisture treatments. (Additional data on E_a/E_a° and ψ_s was obtained as long as growth chamber was continued to operate.)

A. Evaporative condition A: 70°F, 60% R.H. and 0.18 cal/cm^2/min light intensity.

N days 1	$E_a/$ E_a° 2	ψ_s (-J/kg) 3	R.T. % 4	ψ (-J/kg) 5	ψ_a (-J/kg) 6	ψ_p (+J/kg) 7	t 8
1) ψ_s = -10 J/kg							
	1.0	10	94	580	1080	500	
				530	1100	570	
				480	1000	520	
				530	1060	530	25.44**
2) ψ_s = -10 J/kg to -50 J/kg							
1	1.00	10	93	730	1150	420	
				630	1080	450	
				680	1100	420	
				680	1110	430	43.0***
2	.7	50	88	920	1420	500	
				870	1400	530	
				810	1350	540	
				867	1390	523	43.58***
3) ψ_s = -10 J/kg to 100 J/kg							
1	.94	10	93	780	1400	620	
				760	1360	600	
				770	1080	310	
				770	1280	510	5.049*
2	1.0	40	84	950	1270	320	
				1330	1560	230	
				1050	1340	290	
				1110	1390	280	10.586**

Table 4. (cont.)

1	2	3	4	5	6	7	8
	5) ψ_s = -10 J/kg to -1000 J/kg						
0	.83	500		Before irrigation			
1	1.0	15	91	980	1600	620	
				1010	1600	590	
				1070	1900	830	
				1020	1700	680	9.006*
2	1.0	50	87	1450	1900	450	
				1250	1870	620	
				1350	1780	430	
				1350	1850	500	8.038
3	.9	90	84	1680	1880	200	
				1460	1920	460	
				1570	1900	330	
				1570	1900	330	4.40*
4	.83	150					
5	.66	480	81	2090	2200	110	
				1670	2100	430	
				1610	2080	470	
				1790	2127	337	3.008
6	.28	1160	70	2390	2900	510	
				2280	2500	220	
				2200	2400	200	
				2290	2600	310	3.07
7	.75	10					
8	.9	20					
9	1.0	50					
10	.84	90					
11	.8	125					
12	.5	480					
13	.25	1140					

Differences between means of ψ and ψ_a are
* = Significant at 5% level
** = Significant at 1% level

Table 4. (cont.)

B. Evaporative condition B: 86°F, 30% R.H. and 0.18 cal/cm^2/min light intensity.

N days 1	E_a/E_a^o 2	ψ_s (-J/kg) 3	R.T. % 4	ψ (-J/kg) 5	ψ_a (-J/kg) 6	ψ_p (+J/kg) 7	t 8
1) ψ_s = -10 J/kg							
1	1.0	10	93	820 1020 1070 970	1200 1350 1410 1320	380 330 340 350	22.436**
2) ψ_s = -10 J/kg to -50 J/kg							
1	1.00	10	92.6	1030 990 1170 1063	1500 1500 1510 1503	470 510 340 440	8.60*
2	.85	50	91	1340 1580 1100 1340	1540 1680 1640 1620	200 100 540 280	2.10
3) ψ_s = -10 J/kg to -100 J/kg							
	1.00	10	92.5	1190 980 1100 1090	1640 1380 1570 1530	450 400 470 440	10.37**
	.91	50	89.5	1320 1390 1490 1400	1600 1690 1760 1683	280 300 270 283	31.444**
	.87	100	86	1700 1850 1400 1650	1950 2120 1660 1910	150 270 260 260	45.06**

Table 4. (cont.)

1	2	3	4	5	6	7	8
	4) ψ_s = -10 J/kg to -500 J/kg						
1	1.0	10	92	1130	1700	570	
				1230	1800	570	
				1210	1750	540	
				1190	1750	560	56.0***
2	.88	25					
3	.66	50	85	1550	2100	550	
				1600	2050	450	
				1650	2150	500	
				1600	2100	500	17.30**
4	.63	70					
5	.365	120	80.5	1890	2200	310	
				1940	2300	360	
				1900	2250	350	
				1910	2250	340	
7	.21	420	79				
8	.10	540	75.5	2420	2280	-140	
				2430	2360	- 70	
				2425	2320	-105	
				2425	2320	-105	5.19*
9	.84	10					
10	.72	35					
11	.66	70					
12	.65	110					
13	.35	250					
14	.18	390					
15	.066	490					
	5) ψ_s = -10 J/kg to -1000 J/kg						
1	.89	10	92	1070	1680	610	
				1460	1840	380	
				1280	1730	450	
				1270	1750	480	22.325*

Table 4. (cont.)

1	2	3	4	5	6	7	8
2	1.0	45	88.5	1360 1340 1350 1350	1840 1800 1600 1747	480 460 250 397	5.40*
3	.93	80	87	1450 1480 1540 1490	1780 1820 2100 1900	330 340 560 410	5.46*
4	.70	125	77.6	2670 2450 2160 2360	2800 2800 2500 2700	330 350 340 340	58.90***
5	.44	500	75	2650 2700 2600 2650	2740 2810 2700 2750	90 110 100 100	17.33**
6	.22	800					
7	.075	1000	69	2890 2920 2800 2870	2780 2900 2810 2830	110 - 20 + 10 - 40	1.11
8	.86	10					
9	1.0	25					
10	.64	40					
11	.52	75					
12	.46	120					
13	.29	550					
14	.23	650					
15	.21	880					

Differences between means of ψ and ψ_a are
* = Significant at 5% level
** = Significant at 1% level

Appendix B

Propositions

Proposition 1

Plant needs for water can be predicted from critical water potential levels based on the relations of plant water potential to both soil water potential and transpiration rate.

Soil scientists, plant physiologists, and hydrologists engaged in irrigation research have long been attempting to find an answer to a practical question: when should the crop be irrigated? A few years ago, Veihmeyer (1956), proposed a relatively simple answer. Irrigation water should be applied when all the available moisture in the root zone of a particular crop plant has been exhausted.

During the last decade there has been a growing conviction that plant processes which depend on the water status are not determined exclusively by either soil moisture or climate conditions, but rather by their integrated or combined influence (Kramer, 1959, 1963; Vaadia et al., 1961). The energy condition of water in the soil and the desiccating power of the atmosphere determine the internal water status of plants. The internal water condition of plants should, in turn, provide a sound approach to irrigation scheduling, since they reflect both the soil water potential and the desiccating conditions of the atmosphere which can be expressed as potential evapotranspiration. The condition of water in plants, however, is not a unique function of soil water and atmospheric conditions, but it is complicated by the influence of growth stage and physiological condition of the plants. Stomatal activity and functions have a particularly marked influence on the water potentials measured under given conditions (Kettallapper, 1963; Gardner, 1965).

Under constant evaporative conditions, potential evapotranspiration can be fully maintained as the soil dries only if plant water potential (ψ) decreases more rapidly than soil water potential (ψ_s). As soil dries, a stage is reached where ψ falls to a point where accompanying loss of turgor causes stomatal closure and transpiration is reduced. Soil and plant water potentials then tend to converge (Gavande, 1965). A reduction in transpiration by stomatal closure is usually accompanied by a reduction in growth. Consequently, the level of ψ at which growth is first affected and the magnitude of this effect with progressive decrease in potentials in plants and soils is of considerable significance in managing irrigation water.

Relative transpiration rate ($E_a/E_a°$, where $E_a°$ is the maximum evapotranspiration rate under the conditions specified) for orchard grass shows rapid changes between ψ = -1300 Joules/kg and -1750 Joules/kg for low evaporative conditions and between ψ = -2600 and -3200 Joules/kg under high evaporative conditions, according to data in figure 1A. Comparative data of figure 2 from tomato show that most changes in $E_a/E_a°$ occur between ψ = -1200 and -2600 Joules/kg with a 35 percent reduction in $E_a/E_a°$ at ψ = -1750 Joules/kg (low evaporative condition) and at ψ = -2500 Joules/kg (high evaporative condition).

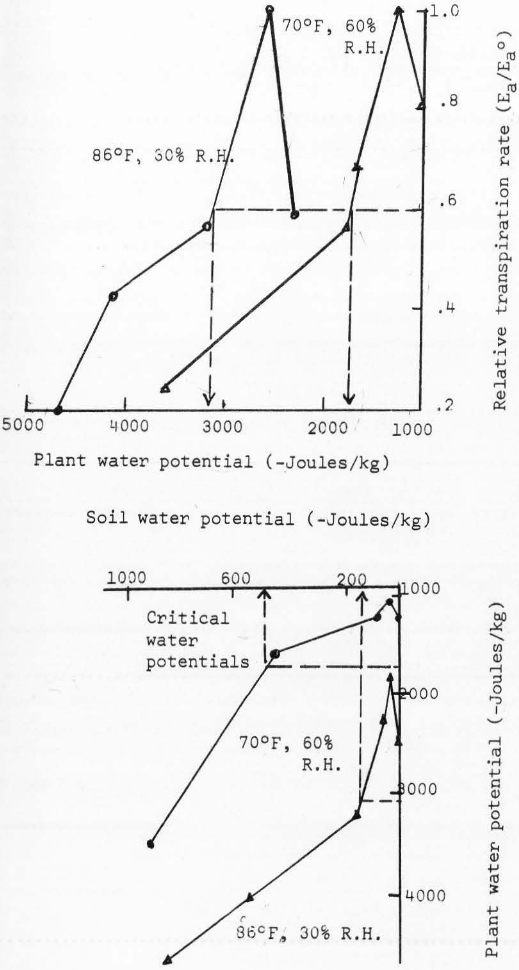

Figure 1. Determination of critical water potentials from A: ψ vs. $E_a/E_a°$, and B: ψ vs. ψ relations for orchard grass.

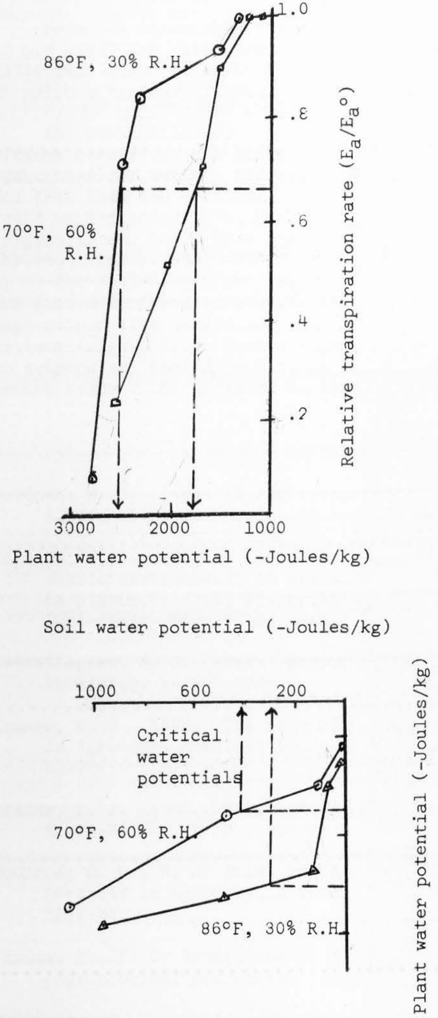

Figure 2. Determination of critical water potentials from A: ψ vs. E_a/E_a^o, and B: ψ_s vs. ψ relations for tomato.

From the relations of $E_a/E_a°$ to ψ, we can hypothesize that the values of $\psi = -1700$ and -3100 Joules/kg for orchard grass and the values of $\psi = -1750$ and -2500 Joules/kg for tomato are critical plant water potentials at which a maximum allowable reduction in $E_a/E_a°$ occurred.

Any combination of atmospheric evaporative and soil moisture conditions resulting in ψ lower than these critical values would indicate plant need for water. All periods during which the plant water potential was less than the critical would be critical periods. Each critical period would be indicated by a corresponding ψ_s for a given evaporative demand (figure 1B and 2B). Thus one should irrigate orchard grass when ψ_s in the root zone reaches -150 Joules/kg under high evaporative demand, and $\psi_s = -540$ Joules/kg under low evaporative demands (figure 1B). Likewise, one should irrigate tomato plants when ψ_s reaches -280 Joules/kg under high evaporative conditions and -400 Joules/kg for low evaporative conditions (figure 2B). Such a dependence of these critical water potentials on evaporative demand conditions thus emphasizes the fact that evaporative demand needs to be included in predicting plant needs for water.

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Proposition 2

The severity of wind erosion as indicated by potential number of dust storms can be predicted from a climatic factor based on effective precipitation and wind velocity.

Wind erosion is active in destroying soil fertility in many arid and semi-arid regions of the world. In the United States, soil blowing has become a major problem in the Great Plains. As new areas are brought into cultivation, the problem increases, since new areas frequently have poorer soils and thinner vegetative cover.

From historical records, we know that periods of drought, wind erosion and dust storms have occurred simultaneously in the Great Plains of the United States. Problems of blowing are most serious during early spring and summer in most arid and semi-arid regions of the world, because high wind velocities occur and the land is usually bare at this time.

Low precipitation, high temperature and high wind velocity have been recognized as contributing factors to increased wind erosion and dust storms (Chepil, 1957, 1963; Zingg, 1957). Dry years are usually accompanied by increased temperature and high wind velocity, whereas wet years are accompanied by lower temperatures and wind velocities. Wet and dry years tend to occur in irregular cycles. In dry periods, wind erosion and dust storms become more serious with time, as the vegetative cover and soil aggregation of cultivated land become progressively poorer each successive dry year. Thus the climatic conditions during at least the three years preceding may be important in influencing the number of dust storms for the current year.

It would be desirable to evaluate major soil and surface conditions that influence wind erodibility of agricultural lands (i.e., field cloddiness, clod stability against abrasion, vegetative residues, surface roughness, wind barriers, width and direction of field). Then one could be prepared to indicate the soil conditions needed to reduce wind erodibility under any given set of climatic conditions.

One major factor, herein called the "wind erosion climatic factor," combines wind velocity and soil surface moisture. To be useful, this wind erosion climatic factor must be directly related to the average rate of wind erosion in different climatic regions.

As the soil particles become more moist, the cohesive force between the particles increases. Therefore, a higher wind velocity is required to move them (Chepil, 1956). Consequently, the soil will erode less the more frequently the soil surface is wetted and the more slowly it dries (i.e., humid region). At the same time, the vegetative cover is likely to be more dense on these soils.

It has been shown that the rate of soil movement by wind, or intensity of wind erosion, varies directly as the cube of wind velocity (Bagnold, 1961; Chepil, 1956), and inversely as the square of effective moisture (Chepil, 1956), or square of effective precipitation (Bagnold, 1945; Zingg, 1956). The effective moisture varies somewhat directly with the amount of precipitation and inversely as temperature (Chepil, 1956)

Wind velocity data for different regions are available from weather records, but information on the moisture of soil surface is not. However, the P-E moisture index (Thornthwaite, 1931) might be used to characterize the soil moisture. If it is assumed that the effective moisture of the surface soil particles varies as the P-E index, then the combined wind erosion climatic factor C may be expressed in percent as that of a climatic factor of a known or standard location as is done by Chepil and others (1963), for Garden City, Kansas.

$$C = 100 \frac{v^3}{(P-E)^2/2.9} \qquad [1]$$

where v = corrected mean annual wind velocity for standard height at 30 feet (by Hellman formula, Thom, 1959), 2.9 $\approx$ average value of $\frac{v^3}{(P-E)^2}$ for Garden City, Kanses, and P-E = Thornthwaite's P-E Index.

Thus the wind erosion climatic factor expressed by equation [1] indicates the relative mean rate of wind erosion that would occur at any geographic location as the percent of mean rate that would occur at a standard station (say Garden City, Kansas, in this particular case), if conditions of soil other than climate were the same. In this particular study, they assumed that (a) the value of C_1 was computed on an annual basis for June 1 to May 31, (b) the number of dust storms during any year is largely influenced by the climatic conditions of at least the three previous years. Hence, a three-year running average of the climatic factor (C_3) was plotted against the number of dust storms (number of days in which dust storm was reported) occurring during the current year. Thus the average value of C_1 for each of the three 12-month periods ending May 31 of 1959, 1960, and 1961, was plotted against dust storms for the calendar year 1961. Further, the average value of C_1 for each of these three 12-month periods ending May 31 of 1959, 1960, and 1961, served as an index of the potential number of dust storms during the calendar year 1962. The greater the annual number of dust storms, the more severe they were.

The relation between the number of dust storm days, i.e., days in which dust storms occurred, and climatic factors for each calendar year for Dodge City, Kansas, and Garden City, Kansas, are shown in figures 1 and 2. Both areas are located in one of the most serious wind eroded areas of the Great Plains. At both places the high incidence of dust storms during the 1930's and 1950's was associated with high climatic indices, whereas the low incidence of dust storms during the 1940's was associated with generally low climatic indices.

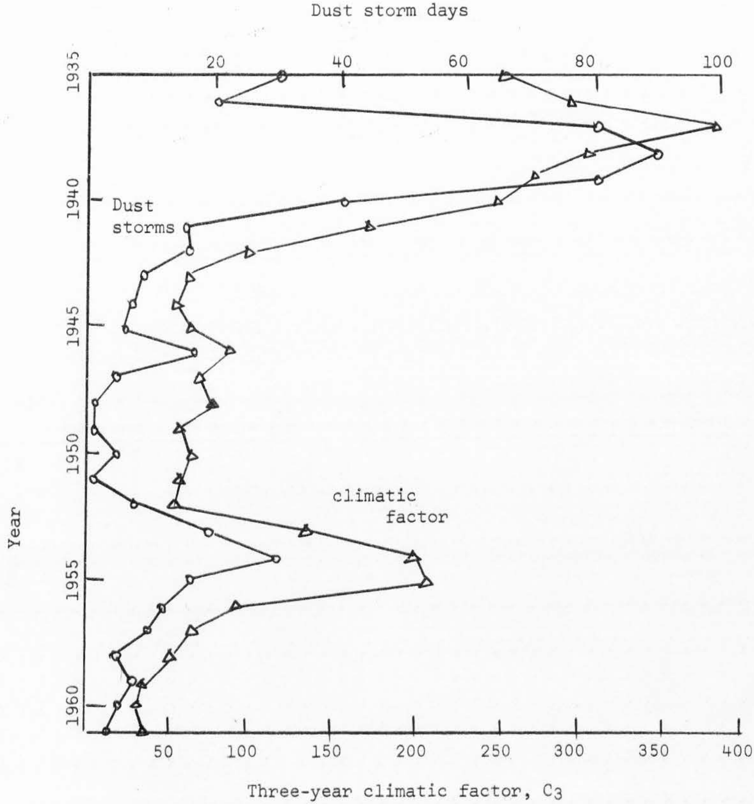

Figure 1. Number of dust storms and climatic index, C_3, for each year of record for Garden City, Kansas.

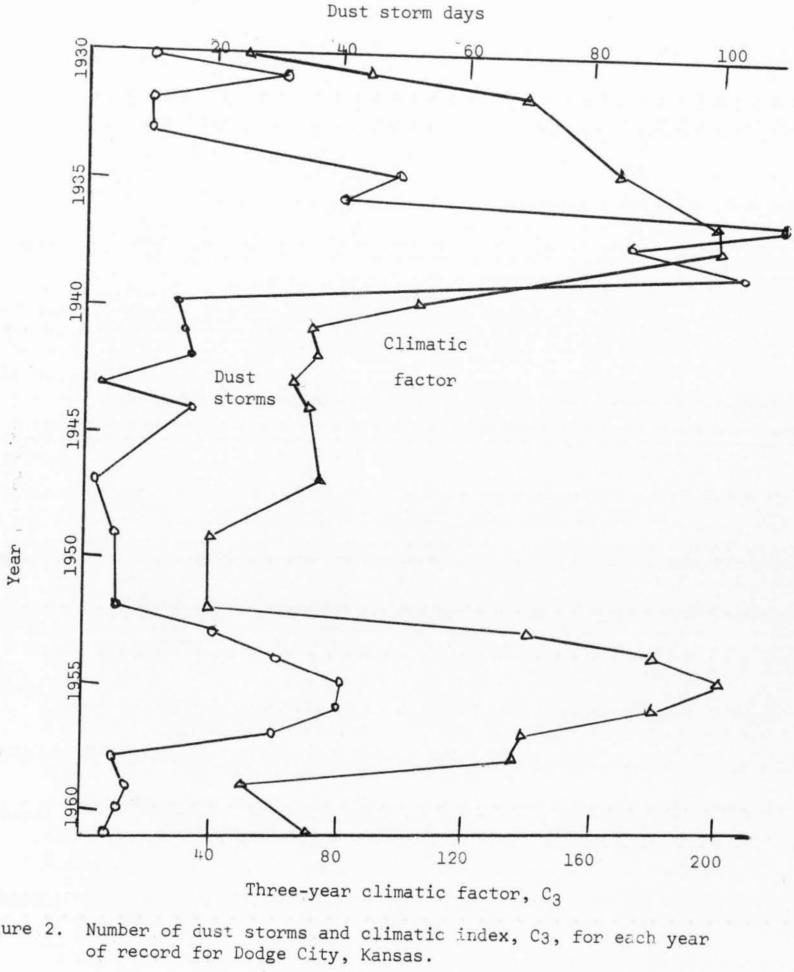

Figure 2. Number of dust storms and climatic index, C_3, for each year of record for Dodge City, Kansas.

In general, the predicted number of dust storms follows the same general pattern as the actual number. Thus the predictions would have indicated more severe dust storms during the 1930's, less severe in the 1950's, and relatively few in the 1940's and 1960's, although some discrepancies occurred.

Predictions of potential number of dust storms could be done roughly at least six months ahead of their occurrence. All that is necessary is to compute wind erosion climatic factor, C_3, for areas such as Garden City, Kansas, based on precipitation, temperature, and wind velocity for three consecutive annual periods, June 1 to May 31.

For certain periods (1930's and 1950's) of severe wind erosion, conditions at both stations generally had the wind erosion climatic factor $C_3 > 125$ (i.e., 25 percent more was predicted than actually occurred). Therefore, if prediction should indicate a potential number of dust storms exceeding 125, extremely serious wind erosions might occur, and farmers might take special precaution to control them. On the other hand, if prediction indicates 25 or less potential dust storms, no special precaution is required.

The data show that only 7 out of 64 (11 percent) predictions were overestimated and 3 out of 64 (5 percent) underestimated. On this basis, prediction may be considered to be about 84 percent accurate.

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Proposition 3

The non-linearity in the relations of ψ_s to ψ can be attributed in part to atmospheric environments surrounding the plant.

Let us examine figure 1, which shows the dependence of ψ on ψ_s under a series of atmospheric evaporative conditions. Under low evaporative conditions (curve —— 2), i.e., at 70°F and 60 percent R.H., the decrease in ψ with decrease in ψ_s is somewhat gradual over most of the soil water potential range; whereas under high evaporative conditions (i.e., at 86°F, 30 percent R.H., curves-3), at first there is a rapid reduction in ψ with a decrease in ψ_s till ψ_s reached a particular value, and then a less rapid decrease below that range. This is logical, since high atmospheric evaporative demand in terms of high temperature and low humidity increases leaf temperature, which in turn increases the steepness of the saturation vapor pressure gradient between the leaf and the air, thus increasing transpiration. Increased transpiration, in turn, decreases plant turgor by lowering relative leaf water content, and develops and steepens water potential gradient between the plant and the soil. Further, as the soil continues to dry a state is reached where ψ becomes sufficiently low that stomata close and thus causing greater resistance to water loss. This changes the slope of the ψ vs. ψ_s curve. Thus the higher the evaporative demand, the water potential gradient between the soil and the plant tends to be steeper up to a certain ψ_s range and less steep below that range.

Conversely, under low evaporative demand conditions, the temperature gradient and consequently the saturation vapor pressure gradient between leaf and air will be less steep over the entire range. As a result, the transpiration will decrease more or less uniformly with ψ_s over a wider range. Thus, the decrease in turgor with decrease in ψ_s will be uniform and the stomatal resistance will be normal over most of the ψ_s range. Thus there is a tendency for the ψ vs. ψ_s curve under low evaporative conditions to tend more towards linearity.

From this explanation, it is probable that there exists a certain low hypothetical--nearly saturated or limiting ideal--atmospheric evaporative condition (like curve 1, dotted line) where decrease in ψ with decrease in ψ_s would be uniform or somewhat linear. Likewise, there exists another extremely high evaporative condition (something like curve 4) where this decline in ψ with ψ_s would be highly deviating from this hypothetical linear relation between ψ and ψ_s.

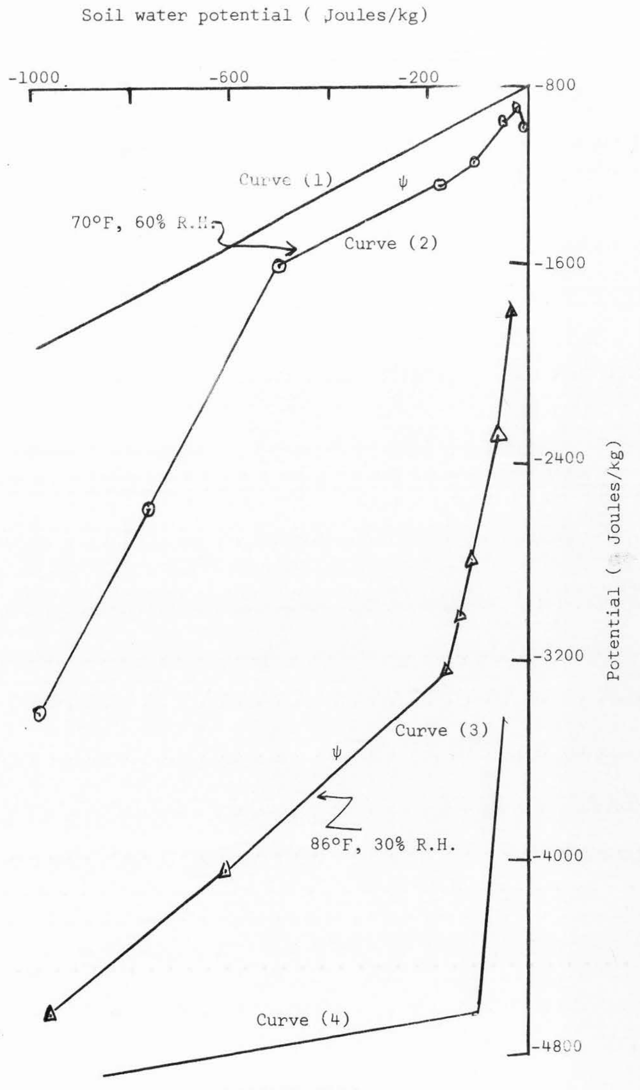

Figure 1. Relation of soil moisture potential to plant water potential for orchard grass under two evaporative conditions.

LITERATURE CITED

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The major objective of this study was to investigate the influence of soil water potential and atmospheric evaporative demand on transpiration loss rates and the components of plant water potential.

Orchard grass and tomato plants grown in a controlled environment chamber were subjected to five soil moisture and two atmospheric evaporative conditions. First, the growth chamber was maintained under constant conditions of 70°F, 60 percent R.H. and 0.18 cal/cm^2/min light radiation. Second, the environmental conditions were changed to a constant condition of 86°F, 30 percent R.H., and 0.18 cal/cm^2/min light radiation (for another set of measurements). The different soil moisture regimes were established by applying irrigation water when soil water potential (ψ_s) in the pot reached: -10 Joules/kg, -50 Joules/kg, -100 Joules/kg, -500 Joules/kg, and -1000 Joules/kg.

The total plant water potential (ψ) and the osmotic potential (ψ_a) on plant leaf sections were measured with a wet-loop vapor pressure psychrometer. The total plant water potential was obtained from living tissue and the osmotic potential from the frozen tissues. Simultaneously, daily fluctuations of relative turgidity, soil water potential, and transpiration loss rates were measured.

The total plant water potential (ψ), the osmotic potential (ψ_a), turgor potential, (ψ_p), and the transpiration losses from the two plant species were influenced by both soil water potential and atmospheric demand. The effect was greater on ψ_a than on either ψ or ψ_p.

Both transpiration rate and plant water potential tend to follow soil water potential but lag behind it. The respective differences were significant between time and plant water potential, soil water potential and transpiration rate for the two species, orchard grass and tomato. The combined effect of atmospheric evaporative demand and soil water potential was more marked than either effect alone. High evaporative demand caused a more marked influence on the plant moisture retention and transpiration than occurred under low evaporative demand conditions. The influence of the atmospheric environment was more marked in moist soil (high ψ_s) than in drier ones.